Silica Sands in the Fort McMurray area, Alberta

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Note: Great Canadian Oil Sands Ltd. (GCOS)
became Suncor Inc. on August 22, 1979.

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ABSTRACT

Tailings sands, waste sand from the processing of the Athabasca Oil Sands, average 95 to 98 percent silica (SiO_2) in the raw bulk samples. These sands, together with other high quartz sands in the Fort McMurray area including McMurray Formation sands where the formation is not impregnated with bitumen, alluvial (bedrock channel) sands from the Clearwater River valley, and dune sands, were studied for their potential as a source of silica sand for glass manufacture and other uses.

The main contaminants of the tailings sands are the residual oil film, the "fines," the iron content, and mica. After beneficiation, the tailings sands analyzed 98 to 99 percent silica (SiO_2), with iron contents of 0.02 to 0.04 percent Fe_2O_3, well within range for high quality glass manufacture. Mica is present in minor amounts but may not have to be removed.

There should be few constraints in the exploitability of this otherwise wasted "byproduct." The little or no mining costs, easy access, and unlimited quantities should more than compensate for the costs of beneficiation.

The alluvial (bedrock channel) sands, located within easy access of Fort McMurray, are also a good potential source of high quality silica sand. After beneficiation, silica (SiO_2) is over 98 percent and iron content (Fe_2O_3) is 0.03 to 0.05 percent. Iron is the main contaminant; mica is not present. These sands are well sorted and within the specified size range for glass and glass fiber manufacture.

In some ways the alluvial sands are superior in quality to the oil sand tailings. However, they do lack the ready availability of the tailings sands, in that exploitation would involve dredging, and thus there could be environmental constraints.

Most of the dune sands tested are well sorted, fine- to medium-grained, and generally of better quality than dune sands elsewhere in the province. One dune sand sampled in the Clearwater River valley has a silica content of over 98 percent SiO_2 and an iron content of 0.04 to 0.05 percent Fe_2O_3 after beneficiation. However, this deposit is far from Fort McMurray, with difficult access, so it is of purely academic interest at this time. Other dunes of lesser quality are located near Fort McMurray and could be considered as sources of sand for industrial or construction uses.

The non bitumen-saturated McMurray Formation sands are very high in quartz, ranging from 97 to 98 percent SiO_2, and have iron contents as low as 0.01 percent Fe_2O_3 after beneficiation. Mica is a major problem and would have to be removed to bring these sands to glass grade quality. Exploitation is uncertain as overburden is thick in many localities, and access difficult. Overall, the unsaturated McMurray Formation sands are not considered a potential source of silica sand.
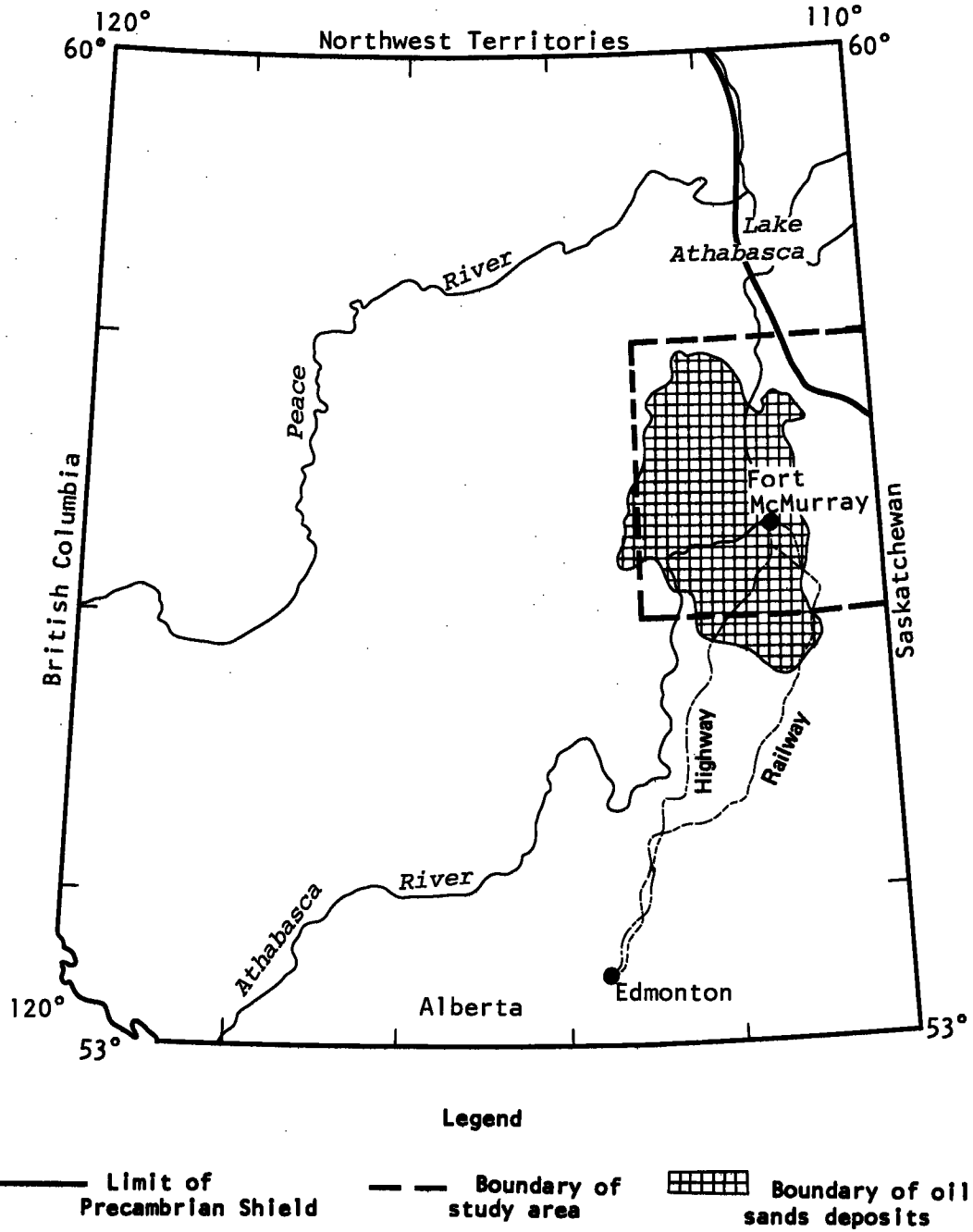
FIGURE 1.   Location of study area and Athabasca Oil Sands deposit

INTRODUCTION

PURPOSE AND SCOPE OF STUDY

Sand tailings accumulate in enormous quantities as waste from the processing of the Athabasca oil sands in northeastern Alberta. From the time of the first experimental efforts to recover the bitumen from the oil sands, these tailings have attracted attention as a potential source of glass sand because of their high silica content. Now that the oil sands are being developed, the ready availability of the tailings sands in virtually unlimited quantities has created even greater interest. This, together with a growing demand for high-grade silica sand in Alberta, prompted the Alberta Research Council to reexamine the economic mineral potential of the tailings sands.

Since the first published work on the tailings sands, by Ells (1914), the Federal and Alberta governments and industry have made preliminary studies of this resource. This report updates the results of these studies with information obtained in the context of actual operating conditions of oil sand processing. This study also presents data on other sources of silica sand in the Fort McMurray area, to permit a comparative evaluation of these materials as alternative silica sand sources. Twenty-nine sand samples were collected from the following sources: tailings disposal sites of oil extraction plants,[1] the McMurray Formation sandstones outside the oil sand area (where the formation is not impregnated with oil), alluvial sand deposits in a bedrock channel underlying the Clearwater River valley, and eolian deposits in several dune fields in the general area.

ACKNOWLEDGMENTS

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GEOGRAPHIC SETTING

The study area (Fig. 1) is in northeastern Alberta, in the northeast lowlands region of the Interior Plains, marginal to the Canadian Shield. It extends from the Saskatchewan

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[1] The GCOS plant, plus earlier commercial and experimental plants.

border west to about 113 degrees longitude, and from about 56 to 58 degrees latitude. Fort McMurray, the main population center, is situated at the confluence of the Clearwater and Athabasca Rivers. The population of Fort McMurray has grown dramatically from 2000 in 1963 to about 22,000 in 1976; the major factor contributing to this growth has been the development of the Athabasca Oil Sands. The only other population center in the study area is Fort MacKay, with about 400 residents, which is situated on the west bank of the Athabasca River about 35 miles (56 km) north of Fort McMurray.

Fort McMurray is served by Highway 63, which links the town to Edmonton 273 miles (439 km) to the south. An extension of Highway 63 (963) continues northward to Fort MacKay, and terminates at the Ells River; both the Great Canadian Oil Sands (GCOS) plant and the Syncrude development are served by this highway. A number of secondary roads in the area service oil exploration and forestry activities.

The country surrounding Fort McMurray is relatively inaccessible during the summer months. Widespread muskeg and swamp prevents the use of most existing roads and trails, except in winter when the ground is frozen.

Freight and passenger service from Edmonton, 300 rail miles (483 km) south, to Fort McMurray is offered by Northern Alberta Railways. The company's intermodal (truck and rail) terminal is located south of Fort McMurray at Linton.

The Athabasca River north of Fort McMurray is navigable by large craft during the summer months. This waterway is used by Northern Transportation Company Limited (NTCL), which operates a barge system in northeastern Alberta from a terminal at Fort McMurray. The Clearwater River, with its many stretches of rough water, can be travelled only by small boats. In winter, the ice on both rivers is thick enough to support most land vehicles.

PREVIOUS STUDIES

Earlier investigations of silica sand in the Fort McMurray area were mainly of the waste sand from the oil extraction process. Ells (1914) discussed "sands extracted from the Alberta bituminous deposits" as a possible source of glass sand and gave the following analysis:

	Weight Percent
SiO_2	95.50
Al_2O_3	2.25
CaO	0.50
Fe_2O_3	0.35
MgO	0.23
Loss on ignition	1.50
	100.33

He considered that although the waste sand could be used to make colored bottle glass, its iron content would preclude its use in the manufacture of clear glass. He also reasoned that "mechanical purification" would be necessary to remove mica, clay and feldspar, and that the sand would have value only if cleanly separated from the bitumen. Subsequently, Ells (1926) concluded that treating waste sand with solutions of caustic soda and hydrochloric acid could reduce the iron content from 0.35 percent to possibly 0.15 percent.

Lilge (1945) experimented with tailings from two earlier commercial plants, the Oil Sands Limited plant at Bitumount and the Abasand Oil Limited plant near Fort McMurray. He found the Abasand material too fine-grained and too high in TiO_2 to respond favorably to beneficiation. The Bitumount sand, after being tabled and passed through a magnetic separator, was found to be free of mica and low in Fe_2O_3 and TiO_2, although the final product was somewhat finer grained than is desirable for glass manufacture.

Hartman (1966) investigated a sample of tailings sand from an experimental plant in the Mildred Lake area (Cities Service Athabasca Inc.) in an attempt to produce glass-grade sand. Agitation and tabling gave a product analyzing 0.08 percent Fe_2O_3. The tabled product, after being screened to −65+100 Tyler mesh sizes (0.21-0.15 mm), and passed through a magnetic separator, analyzed 0.05 percent Fe_2O_3. Specialized magnetic, attrition, and gravity separation techniques failed to lower the iron content to less than 0.05 percent Fe_2O_3; however, ultrasonic cleaning reduced the iron content to 0.04 percent Fe_2O_3.

Hartman concluded that to use the tailings, it would be necessary to remove the bituminous material, size the sand by screening or tabling, and upgrade the sized fractions by magnetic separation. He suggested that further treatment involving violent agitation or attrition scrubbing would remove some of the remaining iron coatings on the particles.

Only Hamilton and Mellon (1973) have referred to silica sand other than oil sand tailings in the Fort McMurray area. They presented evidence which indicates that a channel-fill deposit of alluvial sand underlies the Clearwater River valley, and gave analyses of the sand taken from Research Council of Alberta Gypsum Test Hole B (13-9-89-5W4) located 35 miles (56 km) upriver from Fort McMurray. At this location the buried channel is cut 140 feet (42 m) into bedrock and filled largely with clean, fine sand. Analyses indicate that the bulk of the sand is of −60+120 (0.250-0.125 mm) mesh size with a silica content of 95.91 percent and an iron content of 0.35 percent

Fe_2O_3. Heavy liquid separation of the −60+230 (0.250-0.062 mm) mesh size material increased silica content to 97.24 percent and lowered the iron content to 0.13 percent Fe_2O_3.

SIGNIFICANCE OF SILICA SAND FOR ALBERTA

Silica sand in the strict quality sense of the term[2] is not produced in Alberta. Sand produced within the province and marketed as silica sand is a comparatively low grade material, preferably called "industrial sand." Alberta's requirements for high grade silica, primarily for use by the glass industry, are met by importing sand, with substantial quantities coming from as far away as Illinois (Fig. 2). The freight costs incurred on these imports are a heavy burden for Alberta's glass industry, and if the dependency on imported raw materials continues, will be a major constraint on the future expansion of silica-consuming industries in Alberta. A silica sand source within the province would be a welcome alternative, particularly for those glass industries wishing to expand operations in central and northern Alberta.

SILICA-CONSUMING INDUSTRIES IN ALBERTA

Glass Industry

The major glass and glass products manufacturers in Alberta at present are Dominion Glass Company Limited at Redcliff, Fiberglas Canada Limited at Edmonton, and Canadian Johns-Manville Company Limited at Fort Saskatchewan and Innisfail (Fig.2). Several other companies operate small glass plants, mainly for manufacturing handmade ornamental products, but their consumption of silica sand is small compared to that of the major firms.

Dominion Glass manufactures glass containers at its Redcliff plant and presently uses silica sand from Selkirk, Manitoba. In the past this company imported silica sand from Illinois. Fiberglas Canada manufactures fiber glass insulation at its Edmonton plant. Because less stringent specifications are applied to the raw materials for this product (see Appendix A), the plant is able to use low-grade silica sand from local sources (beneficiated dune sand from the Bruderheim area). Previously, the company obtained silica from the state of Washington. Canadian Johns-Manville manufactures various fiber glass products at its Fort Saskatchewan plant, using glass rods imported from the United States as a feed stock. The company is producing fiber glass insulation at its new Innisfail plant, using silica sand from Selkirk, Manitoba, the former source of raw material for the Fort Saskatchewan plant.

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[2]The commodity "silica sand" is not precisely defined in terms of purity, but implies sand with a very high quartz (silica) content; for a glass sand, the ideal is 98 percent SiO_2 or better. Sand of lesser SiO_2 content may still be called silica sand depending on its industrial use, but if its purity falls below 95 percent SiO_2 it should be called "low grade" silica sand. The author prefers the

term "industrial sand" for low grade silica sand which has specific industrial applications other than for aggregate and general construction purposes. The term "silica sand" should be restricted to the high grade material that approaches glass sand quality.
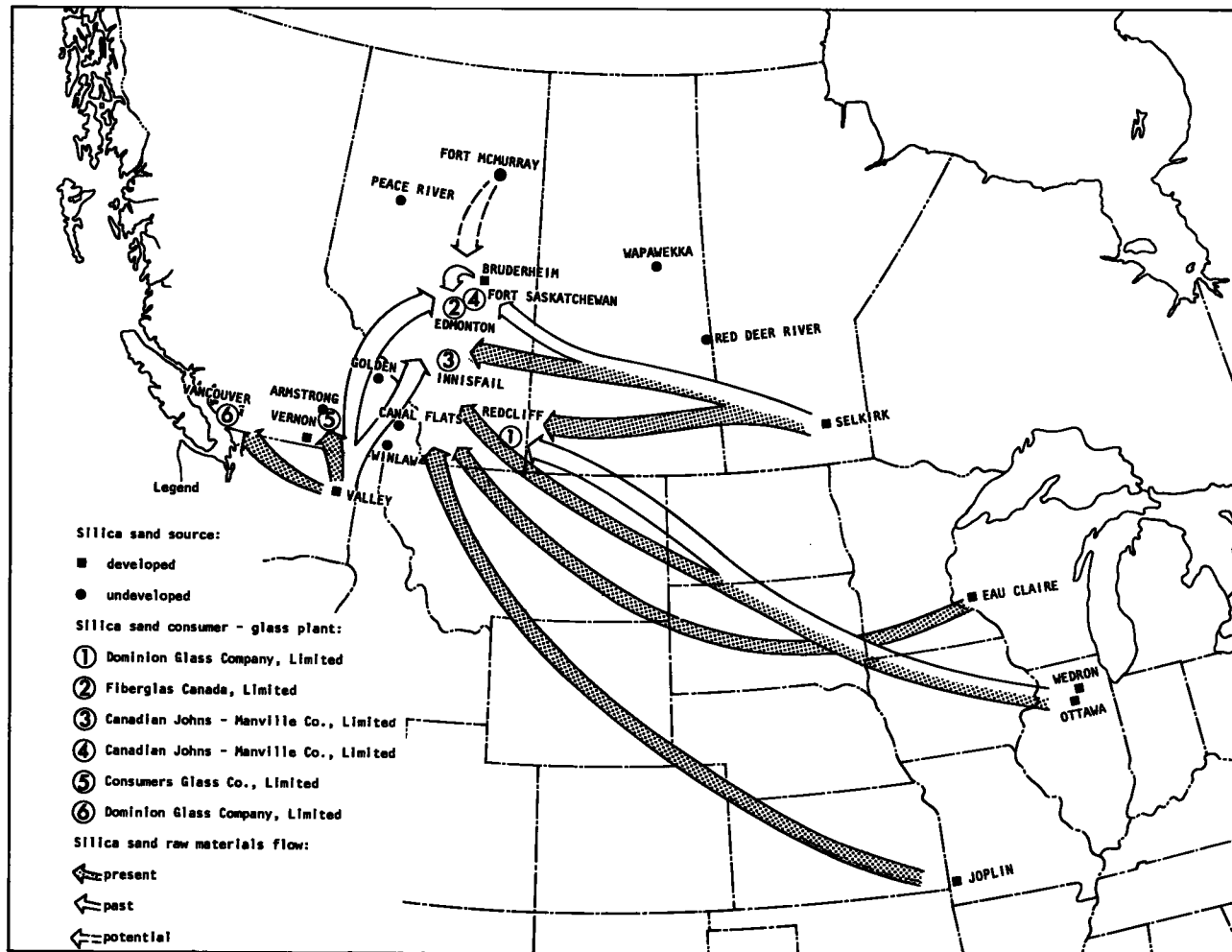
FIGURE 2. Markets and sources for silica sand – Alberta and Western Canada

Alberta's glass industry has been consuming annually about 35,000 tons (32,000 t) of *imported* silica sand. This will likely increase to about 80,000 tons (72,600 t) due to the operations of the Innisfail plant which opened in 1977. In addition, approximately 40,000 tons (36,300 t) of locally quarried sand are used annually by the glass industry. Exact tonnages consumed cannot be ascertained because government keeps such figures confidential when an industry has only a small number of operators.

Other Consumers

Alberta's consumption of silica sand other than in the glass industry is mainly in the operations of hydraulic fracturing, foundries, and sandblasting. In the hydraulic fracturing method of oil and gas well production stimulation, a fracture is induced in the reservoir rock by injecting fluid down the well under high pressure, then sand is injected to "prop" the fracture open. This increases the productivity of the reservoir by increasing the surface area of the wellbore into which hydrocarbons can flow. The annual consumption of sand for this purpose has been highly variable, from as low as 3000 tons (2700 t) in 1964 to a 1977 peak level of over 50,000 tons (45,400 t). With much emphasis now being placed on enhanced recovery methods in petroleum production, this market probably will grow over the next few years. However, as relatively coarse, uniformly sized sand with well-rounded grains (McLaws, 1971) is required, this market may be limited to established import sources. At present, most of the fracturing sand used in Alberta comes from Brady, Texas.

Foundry sand is consumed in Alberta foundries at a rate of about 5000 tons (4500 t) annually. Most of this is silica sand imported from Selkirk, Manitoba, and from the states of Washington and Illinois.

Substantial amounts of sandblasting sand are used in Alberta, but it is difficult to estimate the quantity of silica sand consumed due to the variety of sand types used. Specifications tend to be fairly loose (McLaws, 1971), so that out of approximately 30,000 tons (27,000 t) of sand used annually, perhaps less than 10 percent is actually silica sand. Most is from Selkirk, Manitoba, although some comes from as far away as Wisconsin and Missouri.

Approximately another 25,000 tons (23,000 t) of silica sand are required for a host of other minor uses. These include sand for building and ceramic products, paint and chemical products, furnace bottom linings, filter systems, and commercial ash trays.

SOURCES OF SILICA SAND

Developed Sources

The historical sources of silica sand for the Alberta market are shown by location in figure 2. In general, these sources are operated by well established suppliers who deliver a product

of guaranteed high quality and consistency, and who have been able to maintain a firm hold on the Alberta market despite the long hauls and high delivery costs.

The most important source is Selkirk, Manitoba, which supplies the bulk of the sand consumed in Alberta. Selkirk is also the only Canadian source supplying significant quantities of silica sand to Alberta.[3] Some silica sand, never more than a few hundred tons yearly, has been brought in from southeastern British Columbia.

The Selkirk source, located on the southeast shore of Black Island in Lake Winnipeg, is a deposit of nearly pure quartz sandstone in the Ordovician Winnipeg Formation. Quarried sand is hauled by barge to the processing plant at Selkirk, 80 miles to the south (Collings, 1965), and from there it is transported to Alberta by rail. Selkirk was a source of sand for Alberta as early as 1932 (Minnes, 1967), but only since about 1964 has it been the major supplier. Sand shipped to Alberta from Selkirk now totals about 40,000 tons (36,300 t) yearly.

The silica deposit in southeastern British Columbia (at Oliver) is a vein quartz type, but is now nearly depleted. It was operated primarily as a source of silica for ferrosilicon manufacture and for use as a smelter flux in British Columbia. Some material, in part shipped to Alberta, went into stucco dash, roof chips, and other miscellaneous uses. Although the quarrying operation was shut down in 1968, sales of material for these latter uses has continued from existing stockpiles (Pearse, 1974).

Other important suppliers to Alberta, present or past, are located in the United States; the two main sources are Valley, Washington and Ottawa, Illinois. The Washington source, located about 40 miles (64 km) northwest of Spokane, is a body of quartzite and sandstone found on Lane Mountain near the town of Valley (Carter, Kelly, and Parsons, 1962). This source, like the Selkirk deposit, has been developed relatively recently. Most of the exported production goes to British Columbia, although shipments into Alberta have been significant at times. Current Alberta imports are less than 5000 tons (4500 t) of sand yearly from this source, but during the period 1967 to 1972 they reached as high as 22,000 tons (20,000 t) yearly.

In North America, the silica sand most widely used comes from the Illinois deposit. This deposit was the principal source for Alberta before the Selkirk operation became established. The sand is from the Ordovician St. Peter Formation, a relatively flat-lying sheet-like sandstone body of very great extent, covering about 225,000 square miles (583,000 km²) in six states (Bates, 1960). With an average thickness of 75 feet (23 m), the reserves clearly are immense. The deposit is being

[3]Ontario and Quebec are the major silica producing provinces in Canada, with a combined production of 2 million tons (1.8 million t) out of a 2.7 million (2.4 million t) total for the country in 1974. However, none of this production reaches western Canada.

worked at a number of localities, with the main development centered in northern Illinois at Ottawa and Wedron. This is a long established source, which has current annual production of about 4 million tons (3.6 million t). Imports from this area have been as high as 25,000 tons (23,000 t) annually, but have declined since 1960 and are not significant at present.

Other United States sources indicated in figure 2, that also produce from the St. Peter sandstone, are Eau Claire, Wisconsin and Joplin, Missouri. Both have supplied sand to Alberta in the past.

Undeveloped Sources

Several potential silica sources in western Canada are indicated in figure 2. These are not now developed, but are near enough to service the Alberta market.

The silica deposits in southeastern British Columbia are of the sandstone to quartzite type or vein quartz type and are considered mainly as potential sources of lump silica. Their potential as glass sand sources is low because of the high cost of the crushing, beneficiating, and sizing that would be required to produce glass grade sands. Only the most promising of a number of this type of silica deposits in the region are shown. These are the Golden and Canal Flats deposits (Collings, 1965) and the Armstrong and Winlaw deposits (Burlington Northern Inc., 1972).

The Golden and Canal Flats deposits are in the Ordovician Mount Wilson quartzite, which outcrops extensively along the mountain belt adjoining these two localities. In places the quartzite grades into a sandstone so there are some friable zones. This is the case at Golden and Canal Flats. The deposits are large, and investigation has shown that sand with a high silica content can be produced by procedures that involve crushing, followed by beneficiation and sizing (Collings, 1965). There has, as yet, been no significant production from these deposits.

The Armstrong and Winlaw deposits are in quartz veins or pods associated with intrusive dikes. Silica content is extremely high, but the reserves are limited. Both deposits are suggested to be good prospects for the silicon industry (Burlington Northern Inc., 1972), but as yet no material has been produced from them.

The Peace River deposit in northwestern Alberta lies in the Cretaceous age upper sandstone member of the Peace River Formation. The sandstone is exposed as flat-lying, cliff forming beds along the Peace River valley. The silica sand deposit, located about 7 miles (11 km) north of the town of Peace River, is in a 40 to 60-foot (12 to 18 m) thick friable zone at the top of the sandstone unit (Crockford, 1949). Although the sand is easily upgraded to glass sand quality, the relatively remote location of the deposit has prevented development to date. Potentially limited reserves, and environmental restrictions on operations along the river valley could be further constraints on development.

Both the Red Deer River and Wapawekka Lake deposits in east-central Saskatchewan are part of the Cretaceous Swan River Formation. Both are high in silica and have sizeable reserves (Babey, 1955; Pearson, 1961), but are relatively inaccessible. The Wapawekka Lake deposit lies in unsettled bushland more than 100 miles (161 km) from the nearest rail point. The Red Deer River deposit, although closer to rail, is still far from existing markets. Neither deposit has much potential for the Alberta Market.

POTENTIAL SOURCES OF SILICA SAND IN THE FORT MCMURRAY AREA

Sand exists in great abundance in the Fort McMurray region. In addition to the oil sand tailings, there are several geologically distinct sources of sands which are sufficiently quartz-rich to be considered silica sand. These are indicated diagrammatically in figure 3, which is a generalized stratigraphic column for the region.

BEDROCK SANDSTONES

Athabasca Formation

The Precambrian Athabasca Formation overlies crystalline "basement" rocks in the Shield region to the northeast of the study area (Fig. 4). This formation consists of relatively undisturbed and unmetamorphosed, flat-lying, white to pink marine sandstones and quartzities (Fahrig, 1961). Although rich in silica, the Athabasca sandstone is not considered a potential source of silica sand due to its remote location, but is mentioned here because much of the surficial sands in the area are derived from this unit.

McMurray Formation

The Lower Cretaceous McMurray Formation, the host unit of the Athabasca Oil Sands deposit in the Fort McMurray area (Carrigy, 1973), consists mainly of sandstone. This unit unconformably overlies limestones of the Devonian Waterways Formation, and is overlain conformably by marine shales and siltstones of the Clearwater Formation (Fig. 3). The McMurray Formation, an essentially flat-lying unit, outcrops extensively along the Athabasca and Clearwater Rivers. Thickness varies, averaging about 200 feet (61 m). The sandstones are composed principally of fine-grained quartz, with minor amounts of feldspar and muscovite. The strongly cross-bedded sands are interbedded with silt and clay, and are interpreted to have been deposited in an ancient delta, marginal to the Early Cretaceous sea.

The large portion of the McMurray Formation saturated with heavy oil constitutes the Athabasca Oil Sands deposit (Fig. 4). The potential of the oil-saturated McMurray sandstones as a silica sand source is realized only after the mining and processing of the oil sands to release the sand as relatively

AGE	ROCK UNIT	LITHOLOGY		SILICA SAND SOURCE
RECENT	Postglacial		eolian sands	dune sand
PLEISTOCENE	Glacial	Surficial	lake clays and sands till, sands, gravels	outwash sand
LOWER CRETACEOUS	La Biche Formation		sands	alluvial sand
			clays	
	Pelican Formation		sands	bedrock sand
	Joli Fou Formation		clays	
	Grand Rapids Formation		sands, silts and clays	
	Clearwater Formation		clays	
			sands, glauconitic	
	McMurray Formation		sands, silts (bitumen impregnated in places)	oil sand plant tailings plus bedrock sand (unimpregnated)
UPPER DEVONIAN	Waterways Formation		limestones, shales	
MIDDLE DEVONIAN	Elk Point Group		evaporites dolomites, reefal siltstones evaporitic	
PRECAMBRIAN	Athabasca Formation (Shield)*		sandstones	bedrock sand
	Crystalline Basement		granites, gneisses	

*Athabasca Formation is present only on the Precambrian Shield, northeast of the study area.

FIGURE 3.   *Potential sources of silica sand in stratigraphic context, Fort McMurray area*

clean tailings. Outside the area of oil saturation, the McMurray Formation in its natural state is a potential source of silica sand.

Pelican Formation

The Pelican Formation, a marine quartzose sandstone of Early Cretaceous age, outcrops in the Athabasca River valley southwest of Fort McMurray (Fig. 4). The sandstone unit lies above marine shales of the Joli Fou Formation and below the LaBiche Formation (Fig. 3). The poorly cemented and friable sandstone is composed of well-sorted, subrounded quartz grains deposited in a shoreline environment. The formation is cross-bedded, conglomeratic at the top, and contains lenses of dark gray shale (Wickenden, 1949). At its type locality — the mouth of the Pelican River (Tp. 79, R. 17, W. 4th Mer.) — the formation is described as being an unusually conspicuous white sandstone about 40 feet (12 m) thick. Although at present this deposit is not accessible by road, it is possible that roads will be built to aid oil and gas exploration or forestry activities. Highway 63 is only 25 miles (40 km) away. Thus, the deposit is considered a potential source of silica sand.

SURFICIAL SANDS

Pleistocene and Recent surficial sand deposits overlie bedrock or other unconsolidated deposits in the study area. Most are of glacial origin or are derived from glacial deposits, and tend to vary widely in composition and texture. Although some of these deposits have value for construction purposes, few are sufficiently high in quartz to serve as sources of silica sand.

Outwash

Glacial outwash sand was deposited over much of the Fort McMurray area east of the Athabasca River (Bayrock and Reimchen, 1973). The sands are moderately well-sorted and contain a relatively high proportion of feldspar and dark mineral grains. Outwash sand deposits are unlikely sources of silica, but any deposits located on access roads close to centers of population could possibly supply lower grade silica suitable for blasting sand and for a variety of construction purposes.

Eolian

Dune sands, common in the area, were derived from the widespread sandy glacial deposits through prolonged wind action following deglaciation. These sands are well-sorted, generally fine- to medium-grained, and more siliceous than the parent material from which they were derived. They are particularly widespread in the northern part of the study area adjacent to the Athabasca River valley, and in the southwest, also adjacent to the Athabasca River (Fig. 4). Some dunes of remarkably high silica content are present in the Clearwater River valley in the eastern part of the study area. The dunes, now stabilized, vary from 10 to over 30 feet (3 to over 9 m) in height.

Alluvial

Alluvial sands and gravels are found along major rivers either in the river beds, or as older terrace deposits above present river levels. Stream alluvium consisting mainly of sand is found in valleys of the Athabasca and Clearwater Rivers (Bayrock and Reimchen, 1973). These sands are generally of low quality, but could have some value as industrial sands or for construction purposes. However, a buried river channel containing sand of excellent quality is known in at least three localities along the Clearwater River (Hamilton and Mellon, 1973) and is a potential source of silica sand.

SOURCES SELECTED FOR STUDY

Of the geological sources of sand described, only those judged to have the best potential as sources of silica sand were selected, along with the tailings sands, for detailed study and comparison. They are:

(1) oil sand tailings;
(2) bedrock sandstones from the McMurray Formation (where the formation is not impregnated with oil);
(3) alluvial sands from the buried bedrock channel in the Clearwater River valley;
(4) eolian sands from dune fields in the area.

Twenty-nine samples were studied: four of tailings sands from four different plant sites; five of McMurray Formation sandstones from a single outcrop section; seven of bedrock channel alluvial sands from three auger testholes in the Clearwater River valley; and thirteen of eolian sands from various sand dune localities. Sample locations are shown in figure 4 in relation to their geologic setting.

Methods of Study

The methods and laboratory procedures followed in this study are indicated schematically in figure 5. A more detailed explanation is given in Appendix B. In general, the study methods involved mechanical analyses of all samples to determine grain size distribution, followed by petrographic examination of each fraction to determine mineralogical content and such textural features as grain shape, surface texture, and the nature and amount of coatings and inclusions of impurities. Clay minerals were identified by X-ray diffraction analysis. Chemical analyses were made of all samples (both raw and washed) and of selected size fractions of certain samples. Further chemical analyses were made following beneficiation treatment of selected samples to remove contaminants (magnetic and heavy mineral separations, acid leaching), in order to determine the effectiveness of these treatments in upgrading the sand to glass sand quality.[4]

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[4]The specifications for glass sand are given in detail in Appendix A. Generally, in glass sands the critical impurity is iron, which must be less than 0.05 weight percent Fe_2O_3 in the sand. Silica content must be 98 percent or more.

Analytical Procedures Applied
■ Chemical analysis
● Optical analysis
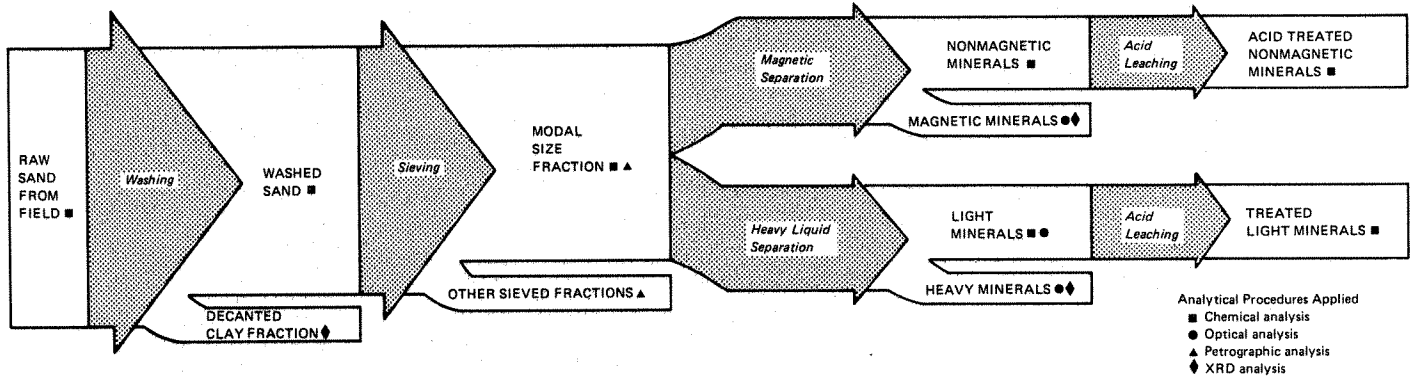▲ Petrographic analysis
♦ XRD analysis

FIGURE 5.   Generalized flow chart of laboratory procedures for study of silica sand samples
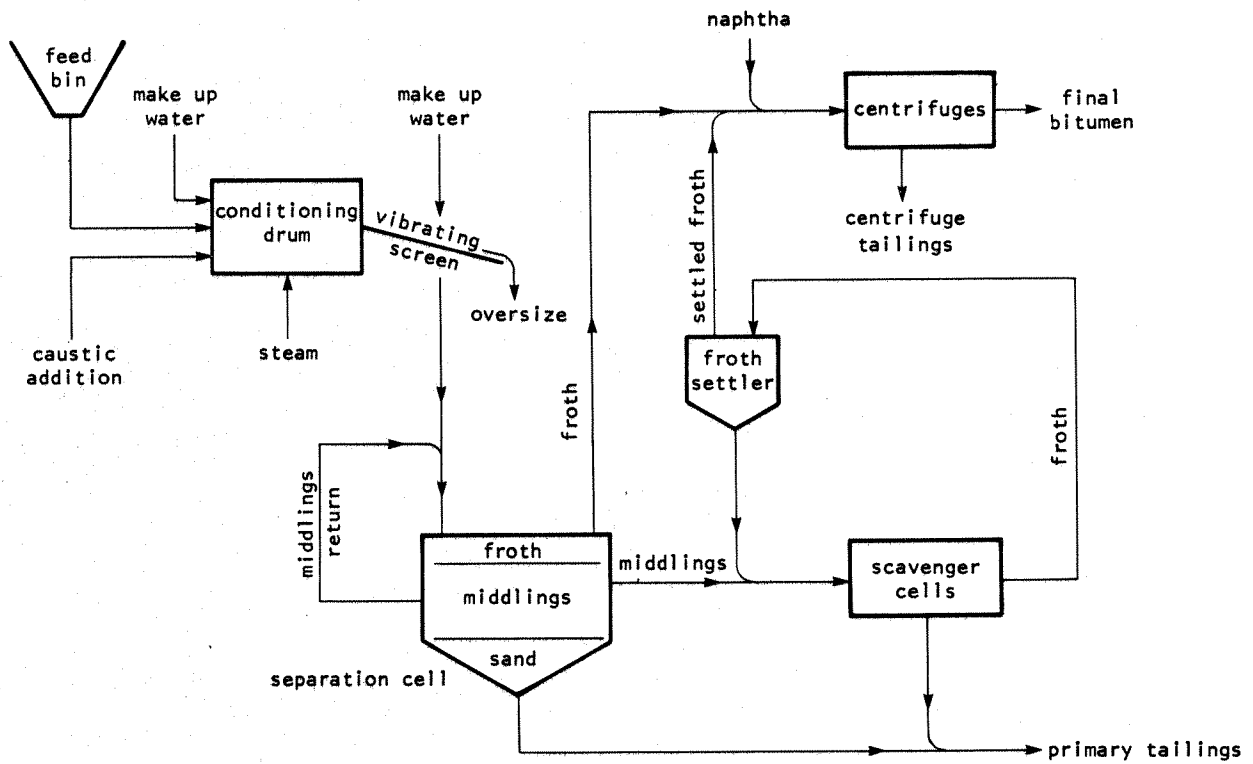

FIGURE 6.   Flow diagram of the GCOS primary extraction process
             (after Allan and Sanford, 1973)

OIL SAND TAILINGS

Oil Sand tailings are the waste sands from the processing of McMurray Formation sandstones from the Athabasca Oil Sands deposit. Each barrel of synthetic crude oil produced requires the processing of 2 tons (1.8 t) of oil sand, of which 80 to 90 percent by volume must be disposed of as tailings. These sands, partially cleaned by the oil extraction process, are very high in silica (95 to 98 percent SiO_2), and are available in virtually unlimited quantities. The tailings sand production from Great Canadian Oil Sands Ltd. is in the order of 100,000 tons (91,000 t) per day and that of Syncrude Canada Ltd., 200,000 tons (181,000 t) per day.

The only bitumen recovery projects in operation are based on open pit mining procedures and a hot water separation process. As Great Canadian Oil Sands Ltd. (GCOS) was the only company operating at the time the research was conducted, particular emphasis was placed on tailings sands from that plant. Figure 6 is a flow chart outlining the primary separation process used by GCOS. The essential steps of the process consist of pulping the oil sand with hot water, steam, and dilute caustic, separating the bitumen from the sand by skimming and froth flotation, mixing the bitumen froth with a diluent (naptha), and centrifuging to remove water and fine solids (McConnell, 1975). The tailings of interest as a silica sand source are the primary tailings. The secondary, or centrifuge tailings (Fig. 6) have no silica potential due to an enriched heavy mineral content (titanium and zirconium minerals are particularly enriched), although the potential for economically recovering these minerals is considerable (Kramers and Brown, 1976; Trevoy et al., 1977).

NATURE OF THE DEPOSIT

The McMurray Formation

The McMurray Formation, as stated previously, is the host rock of the Athabasca Oil Sands deposit. The formation consists of a succession of sands with minor silts and clays, deposited in Early Cretaceous time in an elongate downwarp about 200 miles (320 km) long in the north-south direction and 100 miles (160 km) wide east-west. The present townsite of Fort McMurray is situated near the basin center. The sediments are primarily fluvial and deltaic deposits laid down by a north-flowing river system on an irregular erosional surface of Devonian carbonate rocks (Carrigy, 1967, 1971). The thickness of the formation is variable, averaging 200 feet (61 m) in the study area but ranging from 80 feet (24 m) to a maximum of 390 feet (120 m) at the center of the downwarp. The formation is overlain conformably by marine clays and silts of the Clearwater Formation.

Carrigy (1966) documented a three-fold division of the McMurray Formation within the study area: a lower member of coarse-grained sand and conglomerate; a middle member consisting mainly of fine-grained sand, with very large scale cross-strata; and an upper member of horizontally laminated silts and very fine-grained sands. Carrigy (1971) interpreted the lower sands to be of fluvial origin, and the middle and upper members to represent the foreset and topset beds of an ancient delta. Alternately, the sequence is interpreted as a single genetic unit, with the sloping middle member beds deposited on the inner banks of deep sinuous channels, as epsilon cross-strata (Mossop and Flach, 1977, 1978).

The lower coarse sands are described as mostly quartz and quartzite grains, worn but not well rounded, with minor feldspar and chert grains, and rare flakes of muscovite. The fine-grained sands of the middle member generally constitute 50 percent or more of the succession. These sands are moderately well sorted in large-scale, low angle cross beds. They contain conspicuous amounts of muscovite and more feldspar (up to 5 percent feldspar content) than the lower coarse sands. The very fine sands and silts in the upper member contain a greater percentage of clay-sized material but otherwise have mineral compositions similar to the fine sands. Each member has a characteristic heavy mineral suite: garnet-kyanite-tourmaline-staurolite for the lower member, tourmaline-zircon for the middle, and chloritoid-tourmaline-zircon for the upper member.

Iron-bearing minerals are common throughout the McMurray Formation. These are found in various forms:

(1) as large siderite nodules, at the unconformity at the base of the McMurray Formation;

(2) as siderite spherulites, commonly in the lower coarse-grained sands;

(3) as siderite-cemented siltstones, common as thin beds in the middle member and abundant in the upper member;

(4) as pyrite, either in the form of nodules up to 6 inches (15 cm) in diameter or as disseminated crystals surrounding fossil wood fragments.

Athabasca Oil Sands Deposit

One of the most conspicuous features of the McMurray Formation is the heavy oil saturation that exists in most of the western half of the formation. This huge petroleum reservoir, outlined in figures 1 and 4, is the Athabasca Oil Sands deposit. A small portion of the deposit, at its western extremity, includes some saturated basal beds of the overlying Clearwater Formation.

The Oil Sands deposit as currently outlined covers 5.75 million acres (2.3 million ha) (Alberta Energy Resources Conservation Board, 1963). In a 0.5 million-acre (0.2 million ha) area the oil sands underlie less than 150 feet (46 m) of overburden. This area is indicated in figure 4 as the area suitable for open pit
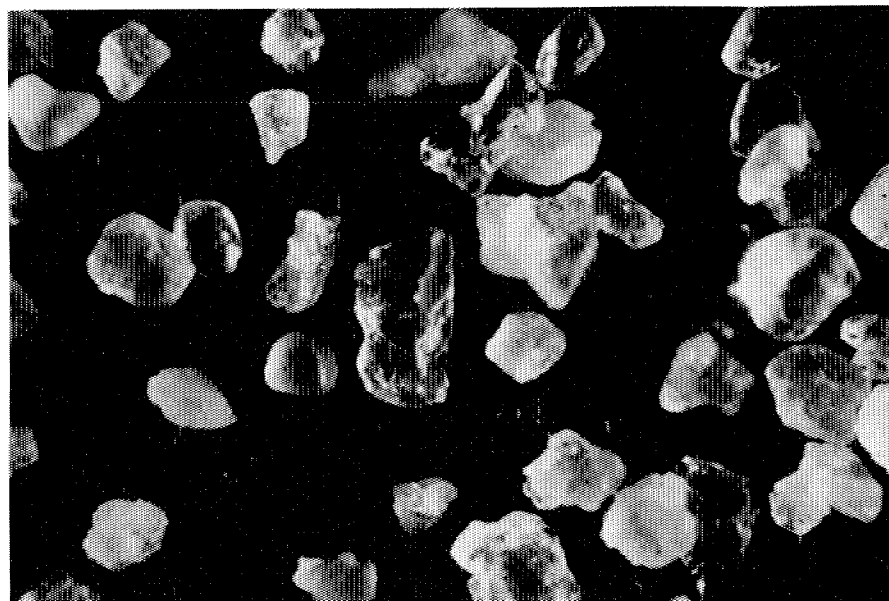
Plate 1.   Photomicrograph of GCOS tailings

mining. Geographic distribution of oil is controlled to the west by the thinning and disappearance of McMurray Formation sediments, to the north by the change from sands to clays and silts, and to the south and east by a conventional oil-water contact (as suggested by Carrigy, 1973).

At the operating GCOS mine, the oil sands orebody averages 130 feet (40 m) in thickness, and consists essentially of oil-impregnated sands with thin interlayers of clay and silt. At this location the general succession of the McMurray Formation includes a lower unit of lenticular beds of conglomerate, sand, shale, and silt; a middle unit of medium- to fine-grained, cross bedded sand; and an upper unit of fine-grained, horizontally bedded sand, with large channels or scours filled with silt beds and siderite-cemented siltstones (Carrigy, 1973). The oil-rich sands that comprise the orebody are found generally in the lower and middle units. Allan and Sandford (1973) describe the orebody as a "basal fluvial sand" unit overlain by "lagoonal deposits"; towards the base the sediments noticeably coarsen and bitumen saturation noticeably increases. Oil saturation in the orebody varies from 8 to 18 percent (by weight), 8 percent being the minimum grade for economic oil sand.

At the GCOS plant, after the oil sands are processed, the tailings are discharged through a pipe in a slurry form into a settling pond.

SAMPLING AND INITIAL TREATMENT

Tailings sand samples were obtained from the GCOS plant and from three formerly operating plants. The GCOS plant and mine, situated about 20 miles (32 km) north of Fort McMurray (Fig. 4), adjacent to the Athabasca River, are located almost in the geographic center of the Athabasca Oil Sands deposit. A tailings sample was collected from the settling pond near the point of discharge of the tailings stream from the primary extraction phase (the so-called Plant 3 tailings). The other samples were taken from tailings disposal areas of the former plants: Abasand Oils Limited, an early commercial plant which operated near Fort McMurray; the Oil Sands Limited (formerly the International Bitumen Company) plant near Bitumount; and the Cities Service Athabasca Inc. pilot plant near Mildred Lake, the site of the Sycrude Canada Limited plant.

The tailings samples invariably contained some residual oil, mainly in the form of a thin film on the grain surfaces but also as highly viscous blobs or masses intermingled with the sand. This residue gives the sand a rather dirty appearance and also causes it to be somewhat sticky, which impairs its handling qualities. Removing the residual oil was a prerequisite to studying the sand in the laboratory, and would be an essential beneficiation step for the successful utilization of the tailings as silica sand. Most of the bitumen blobs and masses can be

screened out of the sand, but the grain coatings must be dissolved or burned off to give a clean, free-flowing material. For this study the samples were boiled in toluene to dissolve the oil residue. Subsequent laboratory procedures are as outlined in figure 5.

PROPERTIES OF THE OIL SANDS TAILINGS

Grain Size and Grain Shape

The results of mechanical analyses of the four tailings samples are tabulated in table 1 and presented graphically in figure 7.

The dominant textural feature of these tailings sands is their fine grain size. The bulk of the GCOS and Cities Service samples fall in the −50+140 mesh size. The Abasand sample is even finer; most of the grains are in the −100+200 mesh size. The Bitumount (Oil Sands Limited) sample is notably coarser than the others, falling mostly in the −50+100 mesh size range. This undoubtedly reflects a difference in plant feed material; the Bitumount tailings probably represent only the richest, basal beds of the orebody while the others represent an average of the whole.

Figure 8 compares the grain size distributions of the four tailings sand samples. In figure 8a these distributions are related to the specified size range for high quality glass sand (−30+100 mesh size). From one third to one half of the sands

in these tailings are too fine for use as glass sand and would have to be separated out and discarded. Figure 8b compares the tailings sands to the desired size range of sands for fiber glass insulation manufacture (−50+140 mesh size).

Results of grain shape analyses are presented also in table 1 as numerical values representing the degree of *roundness*[5] of the grains. The tailings sands have average roundness values ranging from 0.20 to 0.40, which is typical of most sands and acceptable for most industrial purposes (although far below the requirement for high quality proppant sands used in hydraulic fracturing, which should have a roundness of 0.6 or better). The GCOS tailings are notably less round than the other tailings samples, but otherwise the values are fairly uniform. Only the Bitumount tailings display the progression of roundness with increasing grain size that is characteristic of sands in general.

Plate 1 is a photomicrograph showing the typical assortment of grain shapes found in the GCOS tailings sands.

Mineral Composition

A grain count (100 grains) of the major sand size fractions for each sample indicated that the mineral composition of the tailings sand ranges from 94 to 96 percent quartz with minor feldspar and chert (Table 2). Muscovite is present in all

[5]See Appendix B, p. 35 for *roundness* definition.

Table 4. Chemical Analyses of Various Sieve Fractions of GCOS Tailings Sands

Constituent	U.S. Standard Sieve Number[*] (Wt. % retained)					
	−30+50	−50+70	−70+100	−100+140	−140+200	Glass Grade −30+100
SiO_2	98.07	97.93	98.01	97.61	97.32	97.86
Al_2O_3	0.50	0.68	0.76	1.43	0.85	0.74
Fe_2O_3	0.21	0.11	0.06	0.07	0.13	0.12
TiO_2	0.02	0.02	0.07	0.10	0.26	0.05
P_2O_5	–	–	0.00	0.00	0.01	0.01
MnO	–	–	0.00	0.00	0.00	0.00
CaO	–	–	0.00	0.00	0.00	0.00
MgO	–	–	0.00	0.03	0.00	0.02
Na_2O	–	–	0.02	0.14	0.10	0.02
K_2O	–	–	0.33	0.64	0.36	0.43
L.O.I.	–	–	0.27	0.29	0.42	0.39

[*]The screen size in millimetres (mm) is given in Table 1.

samples in very small amounts. Quartz aggregates, ironstone, rock fragments, and carbonaceous matter are observed in the +20 mesh fractions. Heavy minerals constitute less than 0.1 weight percent in the samples, with rutile and tourmaline being common to all. Other heavy minerals identified include staurolite, magnetite, pyrite, zircon, anatase, and siderite.

In the hot water separation process to recover bitumen from the oil sands, the heavy minerals tend to collect with the bitumen in the froth (Kramers and Brown, 1976, Trevoy et al., 1977), resulting in the removal of much of the heavy mineral contamination from the sands prior to their efflux as primary tailings. (Fig. 6).

The clay fraction of the tailings, averaging about 1 percent of the samples, consists predominantly of the clay minerals kaolinite and illite, with minor chlorite.

Surface Iron Staining

Iron stain on quartz grain surfaces is common in the tailings sands. The stain is due to iron oxide coatings deposited on grain surfaces and in some cases penetrating below the surfaces along microfractures in the grains. In addition, some grains contain tiny inclusions of an opaque, iron-rich mineral, probably magnetite.

A measure of the degree of iron staining observed in the tailings sands is given in table 2. The numbers of quartz grains that have staining or inclusions are determined from 100-grain counts, and the intensity of stain is estimated for each grain. Where the stain covers less than half the grain surface in a thin, spotty, or patchy manner it is termed "light." Where it covers more than half the surface in a more-or-less continuous coating but still leaving the quartz grain transparent it is "medium." Staining of intensity sufficient to render the grain opaque or translucent over half or more of its surface is classed as "heavy." Grains with inclusions but no staining are counted separately. The data in table 2 indicated that from 50 to 75 percent of the grains in the tailings sands have iron staining, mainly of the light to medium category, with the GCOS tailings exhibiting the least amount of stain.

Chemical Composition

Results of chemical analyses of the tailings sands are reported in table 3, sample numbers 1 to 4. The analyses are for the raw bulk tailings sands, untreated except for the removal of the oil residue, and for the washed *modal fractions*.[6] The results indicate that the tailings from the four different plant sites are all very similar in composition, all having silica contents of about 98 percent. The main contaminants— — alumina, iron oxide, and titiania — are also present in similar amounts in all four samples and in similarly reduced values in the washed modal size fraction of the sands.

The main contaminants are distributed through the various grain sizes of the tailings sands as indicated in table 4. In general, the amount of these contaminants increases in the finer fractions, which accounts for much of the improvement that takes place in the washed model fraction of the sands (Table 3). Alumina is present mainly in the form of feldspar, mica, and clay minerals, and the lower alumina content in the washed modal fraction is due both to the washing out of the clays and the screening out of the fine sands. Titania is observed to be present mainly as rutile, and to a lesser extent, leucoxene. The titania content is slightly less in the washed modal fraction, due apparently to the screening out of the more heavily contaminated fines.

Iron is the most critical contaminant, and is found in the tailings sands in several forms, although the measured iron content is expressed as Fe_2O_3. As noted previously, from 50 to 75 percent of the grains in tailings sand samples are partly coated with a light film of iron oxide. Iron carbonate coatings also are found on a few grains. Some grains, mostly in the coarser (+50 mesh size) fractions, contain opaque inclusions of iron oxide mineral, probably magnetite. The sands also contain discrete particles of siderite, magnetite, and pyrite. These forms all contribute to the iron content, but the main source seems to be the grain surface staining. The lower iron content of the washed modal is due to the washing away of some of the iron oxide coating and the screening out of some iron-rich particles.

BENEFICIATION

The undesirable components of the tailings sands include the residual oil film on the grains; the "fines," present in high amounts; the mica; and the iron-bearing minerals. To bring the sands up to glass sand quality, beneficiation techniques must be geared towards removing these contaminants. In this study most of the beneficiation effort has been directed towards reducing the iron content, which incidentally reduces the titania and alumina contents. The oil film, fines, and mica are contaminants that could easily be removed if the iron content were reduced. The oil residue can be removed readily by burnoff, or by scrubbing with detergent. The fines present a handling problem, but procedures for their removal are fairly standard; screening or one of the various commercial desliming techniques could be used. The mica is a more difficult problem and its removal may require flotation, hydro, or electrostatic separation, or some combination of these techniques. However, the presence of mica may not be as severe a problem as earlier workers had indicated and perhaps may not be a problem at all because the actual amount of mica present is practically too small to measure, although its flaky habit makes it conspicuous. Mica removal is the subject of a more intensive investigation undertaken subsequent to this study and reported in Appendix C. The iron content can be reduced by a number of methods, for example washing, sieving, scrubbing, acid treatment, magnetic and/or heavy liquid separation.

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[6]See Appendix B, p. 35 for *modal fraction*.

Table 5.   Progressive Effects of Beneficiation Treatments on Tailings Sands

Sample Number	Sample Condition*	Constituent (Wt. %)			
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2
1 (GCOS)	Unwashed	97.60	1.07	0.18	0.08
	Washed and sieved (modal fraction)	98.36	0.89	0.05	0.08
	Washed and sieved (glass grade)	98.29	0.74	0.08	0.06
	Minerals removed**				
	Modal fraction – light fraction (heavy removed)	98.29	0.85	0.05	0.05
	Glass grade – light fraction (heavy removed)	98.18	0.79	0.09	0.06
	Glass grade – nonmagnetic fraction (magnetic removed)	98.31	0.59	0.06	–
	Treated with HCl acid***				
	Modal fraction – light fraction	–	0.62	0.04	0.05
	Glass grade – light fraction	–	0.62	0.03	0.06
	Glass grade – nonmagnetic fraction	–	0.67	0.04	–
	Treated with HF acid****				
	Glass grade – light fraction	–	0.48	0.02	0.04
	Glass grade – magnetic fraction	–	0.30	0.03	0.05
2 (Cities Service)	Unwashed	97.97	0.81	0.19	0.07
	Washed and sieved (modal fraction)	98.74	0.60	0.09	0.04
	Washed and sieved (glass grade)	98.50	0.49	0.12	0.03
	Minerals removed**				
	Modal fraction – light fraction (heavy removed)	98.92	0.59	0.10	0.01
	Glass grade – light fraction (heavy removed)	98.54	0.48	0.08	0.05
	Glass grade – nonmagnetic fraction (magnetic removed)	99.09	0.35	0.08	0.02
	Treated with HCl acid***				
	Modal fraction – light fraction	–	0.46	0.04	0.00
	Glass grade – light fraction	–	0.45	0.05	0.05
	Glass grade – nonmagnetic fraction	–	0.45	0.04	–
3 (Abasand)	Unwashed	97.16	1.01	0.12	0.11
	Washed and sieved (modal fraction)	97.83	0.84	0.11	0.10
	Washed and sieved (glass grade)	98.43	0.84	0.09	0.06
	Minerals removed**				
	Modal fraction – light fraction (heavy removed)	97.88	0.78	0.07	0.10
	Glass grade – light fraction (heavy removed)	98.41	0.65	0.08	0.10
	Glass grade – nonmagnetic fraction (magnetic removed)	99.10	0.66	0.07	0.06
	Treated with HCl acid***				
	Modal fraction – light fraction	–	0.74	0.04	0.08
	Glass grade – light fraction	–	0.65	0.04	0.05
	Glass grade – nonmagnetic fraction	–	0.58	0.03	0.02
	Treated with HF acid****				
	Glass grade – light fraction	–	–	0.04	0.03
	Glass grade – magnetic fraction	–	–	0.02	0.04
4 (Bitumount)	Unwashed	97.53	0.72	0.35	0.05
	Washed and sieved (modal fraction)	97.83	0.61	0.26	0.05
	Washed and sieved (glass grade)	97.48	0.70	0.19	0.02
	Minerals removed**				
	Modal fraction – light fraction (heavy removed)	97.50	0.78	0.16	0.05
	Glass grade – light fraction (heavy removed)	–	–	0.10	–
	Glass grade – nonmagnetic fraction (magnetic removed)	98.27	0.59	0.08	0.02

  * See figure 5 for a flow diagram of beneficiation procedures.

 ** The modal fraction was subjected to heavy mineral separation. The glass grade fraction was split into two portions: one portion was subjected to heavy mineral separation, and the other portion was subjected to magnetic mineral separation.

 *** Only samples 1, 2, and 3 were treated with HCl acid.

**** The glass grade – light fraction and the glass grade – magnetic fraction were treated with HF acid *after* being treated with HCl acid. Only samples 1 and 3 were treated with HF acid.

Table 6.   Comparison of Beneficiated Oil Sand Tailings
with Imported Glass Sands used in Alberta

Source	Constituent (Wt. %)			
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2
Fort McMurray, GCOS	99.10	0.07	0.66	0.06
Acid treated	–	0.02	–	0.04
Selkirk, Manitoba	99.19	0.01	0.00	0.08
Valley, Washington	99.43	0.03	0.011	0.05

Outline of Tests Performed

Figure 5 outlines the preliminary beneficiation procedures followed. These procedures were "bench scale," and were performed only to indicate the amenability of the sands to improvement by some of the various beneficiation techniques commonly used by silica sand producers (for further details see Appendix B). Results of the tests performed on the modal size and glass sand (−30+100 mesh) fractions, of the tailings sand samples, are presented in table 5.

Washing and Sieving

After being treated to remove oil residue, the samples were washed in water to eliminate silt and clay fines. A wetting agent, "calgon," was added to the water to wet the grain surfaces and to remove some of the iron coatings. For the beneficiation tests the samples were screened to the modal size, and also to glass sand size (−30+100 mesh). The greatest beneficiation takes place in the washing and sieving (Table 5). In the GCOS sample, the silica (SiO_2) content in the washed, sieved, glass sand fraction was 98.29 percent compared to 97.60 percent in the raw bulk sample; iron oxide (Fe_2O_3) content decreased to 0.08 percent from 0.18 percent; alumina (Al_2O_3) decreased to 0.74 percent from 1.07 percent. The other tailings samples showed similar changes. Titania was reduced only slightly in the GCOS sample but more noticeably in the other samples.

Magnetic and Heavy Liquid Separation

The amounts of magnetic minerals removed at various magnetic field intensities from the sieved tailings sands (glass sand size) are shown in table 2. The results in table 5 are for magnetic separations run at the maximum intensities, that is 1.7 amperes of current on the Franz isodynamic separator, set at a slope of 18 degrees and tilt of 10 degrees. Slight reductions in the alumina and iron contents of all samples were noted, with most reduction taking place in the Cities Service and Bitumount tailings. In the GCOS sample, iron was reduced only from 0.08 to 0.06 percent Fe_2O_3. The main magnetic minerals identified are quartz grains with heavy staining or inclusions, rutile, pyrite, staurolite, garnet, and kyanite.

The heavy liquid separations performed on washed sieved modal and glass sand size fractions produced virtually no improvement. Very few heavy minerals were recovered from the tailings (see Table 2), because most had already been removed during the oil extraction process. Those recovered were identified as rutile, pyrite, staurolite, garnet, kyanite, and tourmaline.

Acid Leach

The iron content was significantly less after the acid leach treatment, in which the washed and sieved modal and glass sand size fractions, with magnetic or heavy minerals removed, were boiled in 1 percent hydrochloric acid (HCl) for 10 minutes. In all samples, the iron content was reduced to below 0.05 percent Fe_2O_3 (Table 5), a value which is acceptable for manufacture of good quality clear glass.

The best values obtained with HCl acid treatment were for the GCOS and Abasand tailings; iron content was reduced to 0.03 percent Fe_2O_3. In order to determine the maximum possible iron reduction for the tailings, samples were boiled in 1

percent hydrofluoric acid (HF) for two hours. This treatment decreased the iron (Fe_2O_3) content to 0.02 percent in both samples — probably the lowest limit to which the iron content could be reduced, and low enough to qualify the sand for plate glass manufacture (see Appendix A). Remaining iron is likely locked within the quartz grains as inclusions or as iron oxide linings in microfractures.

Summary of Results

The results of testing the tailings sands, and in particular the GCOS tailings sands, indicate that the iron content can be lowered by various means, which coincidentally effect a lowering of other contaminants, to a level acceptable for many types of glass manufacture. However, for a commercial scale operation considerable handling of material would be entailed, because from 30 to 50 percent of the sand would have to be discarded to meet glass sand specifications. It may not be necessary to remove the little mica that remains.

In table 6 the beneficiated GCOS oil sand tailings are compared with high quality imported sand being used in Alberta and Western Canada. The beneficiated tailings compare favorably.

It is appropriate to point out here that tailings sand quality can vary from plant to plant, or even from day to day for a single plant. This variability reflects the inhomogeneity of the oil sands feed, and could also depend on the mining methods employed. Generally, the quality is a direct function of grain size; the finer the sand, the greater is the content of "fines" and other contaminants (Table 4). At GCOS the orebody is mined on two separate benches, with the material blended to maintain a uniform plant feed. Should mining one of the benches be interrupted, the feed to the plant could differ from the average feed. However, over a significant time span the plant feed material is fairly uniform, and tailings sand quality can be expected to be reasonably constant for the GCOS plant source.

MCMURRAY FORMATION SAND

The McMurray Formation, outside the area of oil impregnation, is a potential source of silica. Bitumen-free McMurray Formation exists east of Fort McMurray, eastward from about R. 5, W. 4th Mer. (Fig. 4). At the junction of High Hill and Clearwater Rivers, about 40 miles (64 km) east of Fort McMurray (R. 3), an almost complete section of un-impregnated McMurray Formation outcrops. This is a convenient sampling locality for evaluating the formation as a silica sand source. Other sections of the formation closer to Fort McMurray are not as well exposed or are partly bitumen impregnated (Carrigy, 1959, 1960). The outcrop of the McMurray Formation and the area of bitumen impregnation are shown in figure 4.

NATURE OF THE DEPOSIT

The geologic nature of the McMurray Formation is described in detail in the preceding section. The descriptions of lithologies are mostly for material in the bitumen-impregnated areas, but in unimpregnated areas lithologies are similar in every respect except that the sands tend to be unconsolidated without the binding of heavy bitumen. Unimpregnated McMurray Formation outcrops at several localities in the Clearwater and Athabasca River valleys, but complete sections are rare because of the weathering characteristics of the sands. The High Hill River section (Fig. 9) is probably the best exposure available, although the lithofacies succession at this site is not quite identical to that of the classical McMurray Formation in the oil sands area.

SAMPLING

The section of the McMurray Formation exposed at High Hill River (Fig. 9) was sampled at 5-foot (1.5-m) vertical intervals over a thickness of 63 feet (19 m). The samples were combined into five composite samples as indicated in figure 9 for testing and chemical analyses. Details of procedures followed to evaluate the sands are indicated in figure 5, and given in Appendix B.

PROPERTIES OF MCMURRAY FORMATION SAND

Grain Size and Grain Shape

The results of mechanical analyses of samples from the unimpregnated McMurray Formation are given in table 1 and presented graphically in figure 10. These analyses reflect the typical "fining upwards" of the McMurray Formation sands, indicated graphically in figure 9. Sands from the lower part of the section fall mostly in the $-30+70$ mesh size range but grain size decreases upward to fall mostly in the $-70+140$ mesh size in the upper part of the formation.

A comparision of the sand grain sizes with the specified size range for glass and fiberglass manufacture is given in figure 11. The analyses indicate that grain sizes suitable for glass and fiberglass manufacture, and for most other silica sand uses, would be available from this source.

Results of grain shape analyses are also presented in table 1 as numerical values representing the degree of roundness of the grains. The average roundness values for the McMurray Formation sands show relatively little variation, ranging from 0.27 to 0.34. These values are acceptable for most industrial purposes, although well below the 0.6 or better required for proppant sands used in hydraulic fracturing.

Mineral Composition

The mineral compositions of the McMurray Formation sands are given in table 2, based on 100-grain counts of the major sand size fractions. Compositions range from 93 to 98 percent

Legend

Sandstone, fine grained

Sandstone, medium to coarse grained

Sandstone, conglomeratic

Cross-bedded

Silty

Silt/shale lens

Location of sample site

Clearwater
Formation

unexposed

inaccessible

sample   feet

McMurray
Formation

5

0

10

6

20

30

7

40

8

50

9

60

70
unexposed
(Devonian)
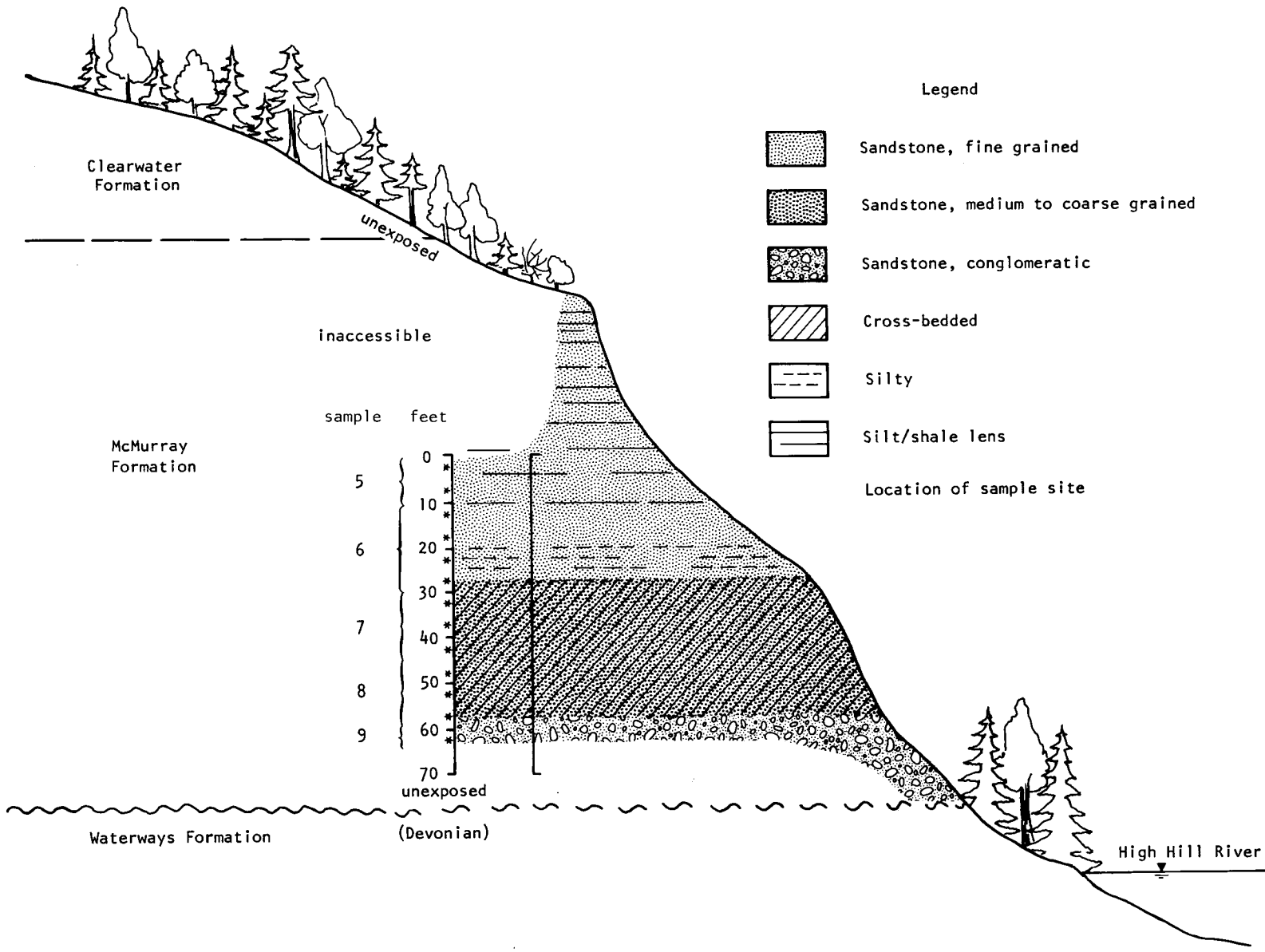
Waterways Formation

High Hill River

FIGURE 9.   McMurray Formation section, High Hill River

quartz with minor feldspar and chert. These sands are noticeably micaceous, particularly in the +50 (0.3 mm) mesh sizes of the upper samples 5 and 6. Samples 7, 8, and 9 have quartz contents of 97 to 98 percent and minor amounts of muscovite. Feldspar content ranges from 1 to 4 percent. Clay minerals in the clay size fraction were identified by X-ray diffraction analysis as kaolinite, illite, and minor chlorite. The heavy mineral content is slightly more than 0.1 percent in the modal sizes (Table 2), and includes tourmaline, rutile, garnet, ilmenite, zircon, staurolite, kyanite, and chloritoid.

Iron oxide staining is present on some of the quartz grains in the McMurray Formation sands. A measure of the degree of iron staining is given in table 2, based on 100-grain counts and visual estimates (as described previously). The degree of staining is relatively low, mainly of the light category on about 65 percent of the grains; from 10 to 40 percent of the grains are clear.

Chemical Composition

Results of chemical analyses of the McMurray Formation samples are given in table 3 for both the unwashed bulk samples and the washed modal fractions. The composition of the sands does not vary to any great degree throughout the section. All sands have silica contents of about 98 percent in the washed modal fraction. The main contaminants, alumina, iron oxide, and titania, also have similar concentrations throughout. Alumina is present in the form of feldspar, muscovite, and clay minerals. Titania is present in rutile, ilmenite, and some brookite. The content of the most critical contaminant, iron, varies from 0.1 to 0.3 percent Fe_2O_3 in the unwashed bulk samples, which is unusually low for a natural sandstone. The iron is mainly present as iron oxide coatings on the grains. Very few grains have inclusions. A few grains are stained and cemented with iron carbonate, and some contain discrete particles of siderite. Heavy minerals such as ilmenite and staurolite may also contribute to iron contamination. The iron content in the washed modal fraction, which varies from 0.04 to 0.08 percent Fe_2O_3, is less than in the bulk sample due both to the washing off of the iron oxide coating and the screening out of some iron-rich particles.

BENEFICIATION

The undesirable components of the McMurray Formation sands are iron and mica. Unlike in the tailings sands, the fines are not a problem, as these McMurray Formation sands more closely approach the desired size range for glass and fiber glass manufacture (Fig. 11). The iron content of these sands is very similar to that of the tailings and can be lowered by the same methods applied to the tailings. Mica is more abundant in the McMurray Formation sands, particularly in the +50 mesh size fractions of samples 5 and 6, and would probably have to be removed by some means. Beneficiation tests were directed mainly toward reducing the iron.

Outline of Test Performed

The beneficiation procedures followed are outlined in figure 5. The results of these tests, performed on the modal size fractions, are presented in table 7.

Washing and Sieving

The silica content of each sample is significantly higher in the washed modal fraction than in the unwashed bulk sand and the iron content less by almost one half. This is similar to results obtained for the tailings sands with the same treatment.

Magnetic and Heavy Liquid Separation

The amounts of magnetic minerals removed from the washed and sieved modal sizes at various magnetic field intensities are shown in table 2. The results given in table 7 are for the maximum intensities used, 1.7 amperes of current on the Franz isodynamic separator set at a slope of 18 degrees and tilt of 10 degrees. Significant improvement was noted in all samples as iron content was reduced to levels of 0.03 to 0.06 percent Fe_2O_3. The main magnetic minerals removed were identified as quartz grains with heavy staining or inclusions, rutile, garnet, ilmenite, tourmaline, zircon, and rock fragments.

Similar results were obtained from the heavy liquid separations performed on separate washed, sieved modal fractions (Table 2). The heavy minerals identified included tourmaline, zircon, rutile, chloritoid, kyanite, and staurolite. A significantly higher weight percentage of heavy minerals was recovered from these sands than from the tailings, because, as discussed previously, much of the heavy mineral content is removed during oil sands processing.

Acid Leach

The sample material remaining after magnetic or heavy liquid separations, was boiled in 1 percent hydrochloric acid for 10 minutes. This removed practically all traces of iron coatings on the grains, reducing the iron content to 0.02 percent Fe_2O_3 or less, well within the range specified for good quality glass manufacture.

Summary of Results

Beneficiation tests on the McMurray Formation sands indicate that the iron content can be lowered by various means to levels acceptable for glass manufacture. However, it would probably also be necessary to remove the excessive amounts of mica present. This might be achieved by flotation, scrubbing and hydroseparation, electrostatic separation, or some combination of these techniques. Screening out the +30 fraction would also remove considerable mica. Other contaminants in the sand, mainly alumina and titania, are present but in amounts small enough to be tolerable.

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Table 7.   Progressive Effects of Beneficiation Treatments on McMurray Formation Sands

Sample Number	Sample Condition*	Constituent (Wt. %)			
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2
5	Unwashed	96.38	1.13	0.23	0.15
	Washed and sieved (modal fraction)	97.50	1.02	0.08	0.15
	Minerals removed**				
	Light fraction (heavy removed)	97.62	0.99	0.06	0.13
	Nonmagnetic fraction (magnetic removed)	97.92	0.80	0.06	-
	Treated with HCl acid				
	Light fraction	97.71	0.89	0.02	0.08
	Nonmagnetic fraction	97.51	0.80	0.02	-
6	Unwashed	96.15	0.94	0.36	0.14
	Washed and sieved (modal fraction)	97.90	0.95	0.08	0.15
	Minerals removed**				
	Light fraction (heavy removed)	98.04	0.81	0.06	0.08
	Nonmagnetic fraction (magnetic removed)	98.12	0.63	0.04	0.02
	Treated with HCl acid				
	Light fraction	97.83	0.88	0.06	0.06
	Nonmagnetic fraction	98.18	0.63	0.01	-
7	Unwashed	97.31	1.28	0.18	0.08
	Washed and sieved (modal fraction)	97.47	1.18	0.07	0.05
	Minerals removed**				
	Light fraction (heavy removed)	97.42	1.01	0.05	0.05
	Nonmagnetic fraction	-	-	-	-
	Treated with HCl acid				
	Light fraction	97.03	0.97	0.02	0.03
	Nonmagnetic fraction	-	-	-	-
8	Unwashed	97.10	0.97	0.11	0.09
	Washed and sieved (modal fraction)	98.71	0.78	0.04	0.08
	Minerals removed**				
	Light fraction (heavy removed)	98.06	0.76	0.03	0.08
	Nonmagnetic fraction (magnetic removed)	97.61	0.70	0.03	0.08
	Treated with HCl acid				
	Light fraction	98.37	0.66	0.02	0.06
	Nonmagnetic fraction	97.58	-	0.02	0.07
9	Unwashed	96.73	1.22	0.18	0.13
	Washed and sieved (modal fraction)	98.02	0.94	0.07	0.07
	Minerals removed**				
	Light fraction (heavy removed)	97.77	0.86	0.03	0.08
	Nonmagnetic fraction	-	-	-	-
	Treated with HCl acid				
	Light fraction (heavy removed)	97.81	0.84	0.02	0.06
	Nonmagnetic fraction	-	-	-	-

* See figure 5 for a flow diagram of beneficiation procedure.

** The modal fraction was split into two parts: one portion was subjected to heavy mineral separation, and the other portion was subjected to magnetic mineral separation.

The sands from the unimpregnated area of the McMurray Formation are similar to the tailings sands originating from processing of bitumen saturated sands. The heavy mineral content is greater in the unsaturated sands, as is to be expected, and muscovite is also more abundant, particularly in the coarser fractions. In the case of the tailings, some of the mica undoubtedly is removed during processing, as mica by virtue of its platy habit and surface tension effects would tend to collect with the froth solids.

ALLUVIAL (BEDROCK CHANNEL) SAND

Clean alluvial quartz sand is found in a buried channel at several places along the Clearwater River valley (Hamilton and Mellon, 1973). Preliminary data on this deposit had indicated a source of silica sand potentially superior in quality to the oil sand tailings. To confirm these preliminary findings, an auger testhole drilling program was undertaken to explore for and evaluate the channel sand near Fort McMurray. The existence of the channel (or some form of sand-filled bedrock depression) was confirmed, and samples of the channel-fill sand were obtained for this study.

NATURE OF THE DEPOSIT

The origin and extent of this "buried channel" in the Clearwater River valley is speculative. It is at least 100 feet (30

m) deep at Fort McMurray as shown by records of exploration wells drilled for salt between 1919 and 1936 (Hamilton and Mellon, 1973). In the present study the auger testholes did not penetrate through the channel due to a depth limitation of 60 feet (18 m) for the auger tool. The portion of the channel penetrated was found to be completely filled with clean white sand from the base of Recent alluvium down to the depth of 60 feet (18 m) (Fig. 12). Thirty-five miles (56 km) up the Clearwater River from Fort McMurray in RCA Gypsum Test Hole B, the channel bottom was penetrated at a depth of 142 feet (43 m), and it was found to be largely filled with similar sand (Hamilton and Mellon, 1973). Although no data exists for the area between Fort McMurray and the site 35 miles (56 km) upstream, the interpretation placed on these observations is that of a continuous bedrock channel, 100 to 140 feet (30 to 43 m) deep, underlying the Clearwater River valley and filled completely or partly with clean white silica sand (Fig. 12). Recent drilling data suggests that this channel underlies the Athabasca River valley as well (D.A. Hackbarth, Alberta Research Council, pers. comm., 1978).

The width of the channel has not been established, but available data indicate that it is narrower than the present valley. The depth of the channel suggests an origin prior to the last episode of glaciation in the region, inasmuch as the elevation of the channel bottom in the gypsum testhole location is almost level with Lake Athabasca, the base level for
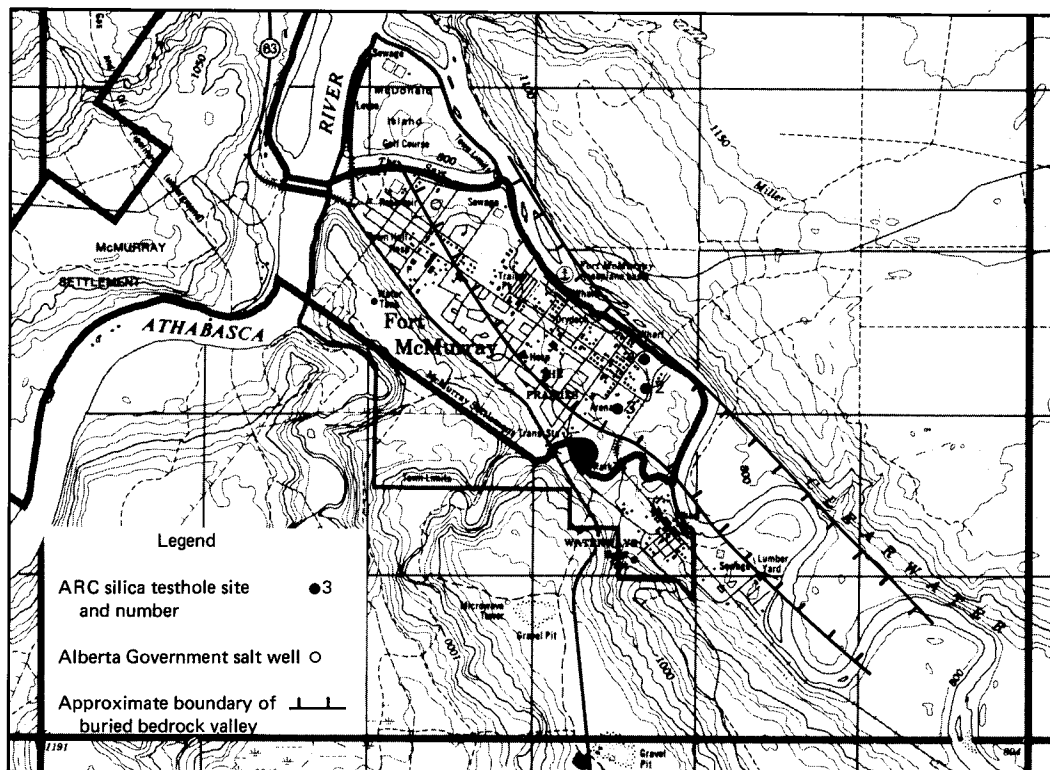

FIGURE 13.   Auger testhole sites

postglacial erosion. It is actually 40 feet (12 m) lower than the bottom of the same channel penetrated at Fort McMurray, which could mean that the preglacial drainage flowed eastward in this valley.

An alternative explanation is that the channel is actually early postglacial in origin; that is, it developed prior to deglaciation of the Lake Athabasca region of the north. Christiansen (1977) suggests that meltwater in the Clearwater drained eastward until that time and was reversed only after the final retreat of the glacier.

The high purity of the channel sand (relative to most glacial and Recent sands in the region) suggests it to be a reworked derivative of the Precambrian Athabasca sandstone lying to the northeast, but no determinative study has been made.

SAMPLING

Three testholes were drilled across the Clearwater River valley as shown in figure 13 and samples were obtained at 5-foot (1.5-m) intervals in each hole. The samples were combined for analysis into the intervals indicated in figure 14. An outline of procedures followed to evaluate the sands is given in figure 5.

PROPERTIES OF THE ALLUVIAL SANDS

Grain Size and Grain Shape

The results of mechanical analyses of the alluvial channel sand samples are given in table 1 and presented graphically in figure 15. Testholes 1 (samples 10, 11, and 12) and 2 (samples 13, 14 and 15) both intersected the deepest part of the channel. The sands in Testhole 1 are fine grained (dominantly −70+140 mesh sizes), and well sorted, becoming finer with depth. Testhole 2 penetrated somewhat coarser sands, dominantly −40+100 mesh sizes, and the lower part (sample 15) is rather poorly sorted. Testhole 3 was on the flank of the channel and penetrated only 30 feet (9 m) of the sand before encountering bedrock. This sand (sample 15) is also mainly in the −40+100 mesh size range.

A comparison of the grain size distributions of the alluvial sands with the preferred size range for glass and fiber glass manufacture is given in figure 16. These graphs indicate that a suitable range of grain sizes exists within the deposit to consider the sands for either use.

Results of grain shape analyses are also presented in table 1 as numerical values representing the degree of roundness of the grains. The average roundness values are fairly uniform for all the samples, ranging from 0.26 to 0.36. All the samples display a slight progression of roundness with grain size, the fine grains having an average roundness of about 0.28, and the coarse grains of about 0.34. These roundness values are acceptable for most industrial sand uses, although well below 0.6 or better required for proppant sands.

Mineral Composition

Grain counts of each sample indicated that the mineral composition of the alluvial sands ranges from 90 to 95 percent quartz and 3 to 7 percent feldspar, with minor amounts of chert and clay minerals (Table 2). The clay minerals in all samples are illite, kaolinite, montmorillonite, and chlorite. Heavy minerals, which form 0.2 to 0.3 percent of the samples, were identified as amphiboles, pyroxenes, ilmenite, tourmaline, zircon, garnet, goethite, biotite, barite, apatite, and hematite. Of these, the first five are common to all samples. Large authigenic overgrowths were noticed on over half the tourmaline grains, another possible indicator of a Precambrian Athabasca Formation source[7] (Mellon, 1956).

Iron oxide stain is common on the quartz grains of these alluvial sands. A measure of the degree of iron staining is given in table 2, based on 100-grain counts and visual estimates as described previously. The data in table 2 indicate that from 60 to 80 percent of the quartz grains in the sands have iron oxide stain of the light to medium category. Opaque inclusions are present in 1 to 3 percent of the grains.

Chemical Composition

Chemical compositions of the alluvial sand samples are given in table 3 for the unwashed bulk sand and the washed modal fraction. The composition did not vary significantly with depth or between testhole localities. All sands have silica contents of about 98 percent in the washed modal fraction. The alumina, iron, and titania contents are fairly uniform, and are comparable to the amounts measured in both the tailings and McMurray Formation sands, except that the alumina content is slightly higher in the alluvial sands. This reflects the greater amount of feldspar as recorded in the mineral grain count (Table 2). The iron content measures close to 0.3 percent Fe_2O_3 in all the unwashed bulk samples. In the washed modal fraction this is reduced by about one half.

These compositions and consistencies are remarkable for alluvial sands deposits, and indicate that the sands could be used without any further treatment for many industrial applications, such as fiber glass manufacture.

BENEFICIATION

The main contaminant of the alluvial sands is iron. The beneficiation tests were directed mainly toward reducing the iron content.

Outline of Tests Performed

The beneficiation procedures followed are as outlined in figure 5. Table 8 presents the results of these tests, showing the improvements in silica sand quality with each procedure.

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[7]See also page 21.
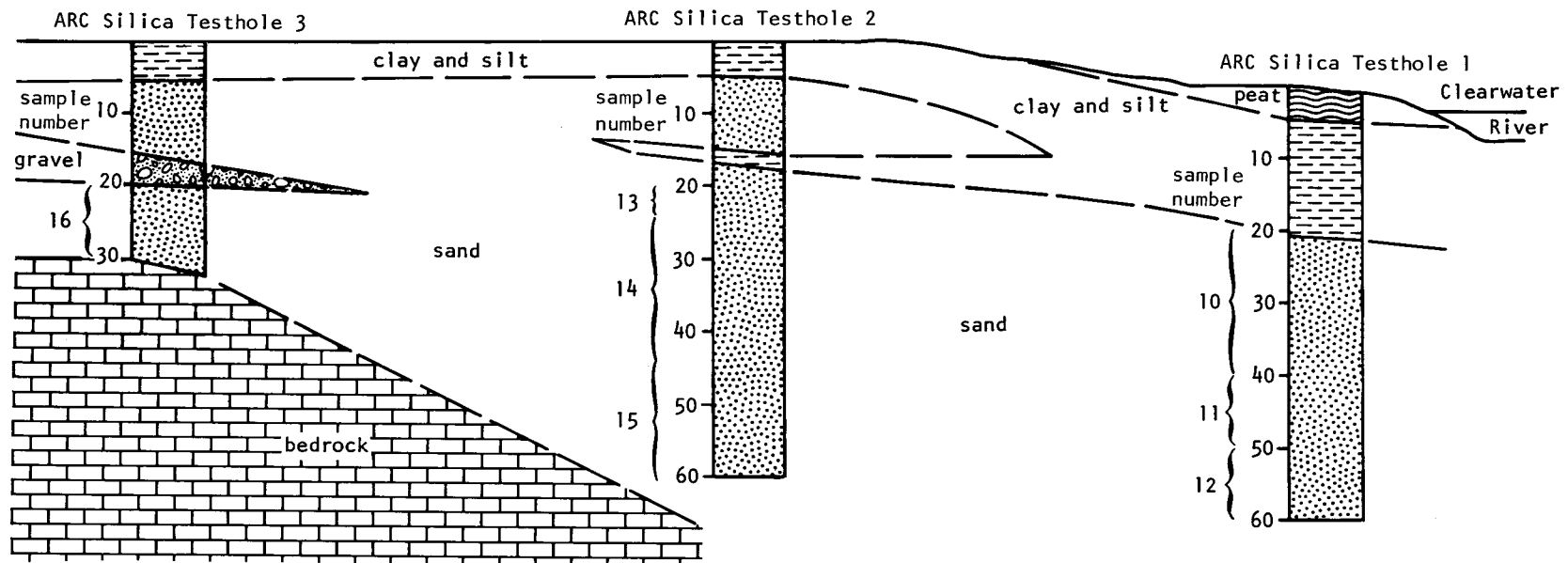
FIGURE 14.   Auger testhole sections of alluvial (bedrock channel) sands

Table 8. Progressive Effects of Beneficiation Treatments on Alluvial (Bedrock Channel) Sands

Sample Number	Sample Condition*	Constituent (Wt. %)			
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2
10	Unwashed	95.68	1.51	0.31	0.07
	Washed and sieved (modal fraction)	97.54	1.16	0.15	0.06
	Minerals removed**				
	Light fraction (heavy removed)	97.46	1.11	0.12	0.07
	Nonmagnetic fraction (magnetic removed)	98.12	0.86	0.06	0.06
	Treated with HCl acid				
	Light fraction	97.78	1.10	0.07	-
	Nonmagnetic fraction	98.20	0.75	0.02	0.06
11	Unwashed	95.95	1.34	0.29	0.09
	Washed and sieved (modal fraction)	97.29	1.38	0.16	0.08
	Minerals removed**				
	Light fraction (heavy removed)	97.20	1.38	0.11	0.04
	Nonmagnetic fraction (magnetic removed)	97.11	1.22	0.08	-
	Treated with HCl acid				
	Light fraction	97.49	1.18	0.08	-
	Nonmagnetic fraction (magnetic removed)	97.37	1.21	0.05	-
12	Unwashed	95.79	1.78	0.29	0.08
	Washed and sieved (modal fraction)	96.01	1.59	0.15	0.07
	Minerals removed**				
	Light fraction (heavy removed)	96.88	1.72	0.12	0.06
	Nonmagnetic fraction (magnetic removed)	96.84	1.36	0.09	0.02
	Treated with HCl acid				
	Light fraction	-	1.45	0.08	0.01
	Nonmagnetic fraction	-	1.57	0.05	-
13	Unwashed	96.34	1.39	0.31	0.06
	Washed and sieved (modal fraction)	97.79	1.12	0.14	0.06
	Minerals removed**				
	Light fraction (heavy removed)	97.75	1.23	0.15	0.03
	Nonmagnetic fraction (magnetic removed)	97.99	0.68	0.07	0.02
	Treated with HCl acid				
	Light fraction	-	0.96	0.09	-
	Nonmagnetic fraction	97.98	0.71	0.03	-

Table 8.   Progressive Effects of Beneficiation Treatments on Alluvial (Bedrock Channel) Sands — Continued

Sample Number	Sample Condition*	Constituent (Wt. %)			
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2
14	Unwashed	97.23	1.27	0.21	0.06
	Washed and sieved (modal fraction)	98.13	1.08	0.13	0.05
	Minerals removed**				
	Light fraction (heavy removed)	97.49	1.01	0.11	0.05
	Nonmagnetic fraction (magnetic removed)	98.13	0.55	0.04	0.06
	Treated with HCl acid				
	Light fraction	-	1.02	0.08	0.01
	Nonmagnetic fraction	-	0.77	0.03	-
15	Unwashed	95.95	1.58	0.30	0.12
	Washed and sieved (modal fraction)	97.18	1.47	0.18	0.09
	Minerals removed**				
	Light fraction (heavy removed)	97.10	1.53	0.14	0.09
	Nonmagnetic fraction (magnetic removed)	-	1.59	0.08	-
	Treated with HCl acid				
	Light fraction	97.15	1.15	0.05	0.03
	Nonmagnetic fraction	-	-	0.08	-
16	Unwashed	96.01	1.02	0.29	0.09
	Washed and sieved (modal fraction)	98.03	0.90	0.10	0.06
	Minerals removed**				
	Light fraction (heavy removed)	98.10	0.92	0.10	0.06
	Nonmagnetic fraction (magnetic removed)	98.24	0.46	0.04	0.04
	Treated with HCl acid				
	Light fraction	98.40	0.79	0.07	-
	Nonmagnetic fraction	98.30	0.54	0.04	0.05

* See figure 5 for a flow diagram of beneficiation procedure.

** The modal fraction was split into two parts: one portion was subjected to heavy mineral separation, and the other portion was subjected to magnetic mineral separation.

Washing and Sieving

Chemical analyses of both the bulk unwashed alluvial sands and the washed modal sizes are given in table 8. Compared to the bulk sample, the washed modal fraction contains significantly more silica, and significantly less iron (0.15 percent Fe_2O_3 compared to 0.3 percent Fe_2O_3).

Magnetic and Heavy Liquid Separation

The amounts of magnetic minerals removed at various magnetic field intensities from the washed, sieved modal fractions are shown in table 2. The results given in table 8 are for the maximum intensities; that is, 1.7 amperes of current on a Franz isodynamic separator set at a slope of 18 degrees and tilt of 10 degrees. The results show that the iron is reduced by approximately one half, from average values of 0.15 percent down to about 0.07 percent Fe_2O_3. Some of the magnetic minerals removed include quartz grains with heavy iron staining or inclusions, magnetite, garnet, siderite, staurolite, and sphene. In Testhole 3 a different assemblage was observed, consisting mainly of magnetite and ilmenite with some geothite.

In the heavy liquid separation tests performed on separate washed, sieved modal fractions there was less improvement in the sand; iron contents (Table 2) were reduced only to an average of 0.12 percent Fe_2O_3. The heavy minerals identified include amphibole, tourmaline, apatite, and biotite.

In the magnetic and heavy liquid separation tests the main beneficiation effect is a reduction in iron content. Alumina and titania are not significantly decreased.

Acid Leach

Acid leaching was performed on the light fraction from the heavy liquid separation, and in a separate test, on the nonmagnetic fraction from the magnetic separation. Samples were boiled in 1 percent hydrochloric acid for 10 minutes. The iron content was reduced from 0.07 percent to about 0.03 percent Fe_2O_3 in the nonmagnetic fraction, well within the range for good quality glass manufacture.

Summary of Results

Beneficiation tests on the alluvial (bedrock channel) sands indicate that the iron content can be lowered by a combination of treatments to a level acceptable for glass manufacture. Other contaminants in the sand, mainly alumina and titania, are present in amounts small enough to be not objectionable. Mica is practically absent.

EOLIAN SANDS

The eolian sands in the area are derived from glacial sands which cover extensive areas in the vicinity of Fort McMurray. These sands, of variable mineral compositions and grain size, were deposited during Late Pleistocene (Wisconsin) time in glaciofluvial and glaciolacustrine deposits, and also in till composed predominantly of sand in the eastern part of the region (Bayrock and Reimchen, 1973). Because of their wind-blown origin, the dune sands normally should be cleaner, more silica rich, and better sorted than the glacial material or parent material from which they were derived and therefore, were included in this study for evaluation of their silica sand potential.

NATURE OF THE DEPOSITS

Sand dune fields in the area have been mapped by Bayrock (1969, 1970) and Bayrock and Reimchen (1973), and are outlined on figure 4. Individual dunes vary from 10 feet (3 m) to more than 30 feet (9 m) in height, and the sheet sands that formed between dunes are from 2 to 5 feet (0.6 to 1.5 m) thick. Most dunes are now stabilized by vegetation, although in many locations where surface vegetation has been stripped, blowouts are present. The shape of the dunes shows that the prevailing wind direction during the immediate postglacial period was from the southeast to east (Bayrock and Reimchen, 1973).

Generally, the dune sands in the Fort McMurray area are of higher quality than dune sands in southern and central Alberta. This is believed to be due to their proximity to the large outcrop area of the Athabasca Formation, from which much of the glacial sand of the area was derived. Even within the study area the sands show a progressive change in quality toward this source area. The sands are variable in composition and texture depending on the nature of the parent material of the glacial sands. They frequently have a significant feldspathic component along with varying amounts of dark mineral grains and iron oxide stain, all of which contribute to a light brown or "dirty" appearance. Purity increases northeastward, and in one area of dunes, developed adjacent to and on the floor of the Clearwater River valley near the Saskatchewan border (sample localities 17, 18, and 27 — Fig. 4), the sands are extraordinarily clean and free from discoloration. These sands are well sorted, coarser than typical eolian sands, and quite unlike dune sands seen elsewhere in the region or in the province.

SAMPLING

Sample locations are given in figure 4. The number and type of samples taken varied, depending on the location and exposure of the deposit. Surface exposures were grab sampled across the dune surface. Where a sectional cut of the dune was exposed, sampling was done at 1-foot (0.3-m) intervals down the face of a cut. Generally, sampling was conducted close to highways or rivers. Other samples obtained from more remote locations are included as examples of dune sands in the area, although their value at present may be doubtful. An outline of the procedures followed to evaluate the sands is given in figure 5.

PROPERTIES OF EOLIAN SANDS

Grain Size and Grain Shape

The results of the mechanical analyses of the dune sand samples are given in table 1 and presented graphically in figure 17. Most are well sorted, fine- to medium-grained sands, but considerable variation occurs. Samples 17 and 18 are well sorted, and medium-grained, with 92 to 94 percent of the sand fraction in the −50+100 mesh size. This is much coarser than the tailings sands and unusually coarse for dune sands. Samples 22 and 23 have over 80 percent of the sand fraction in the same −50+100 mesh size range.

Results of grain shape analyses are also presented in table 1 as numerical values representing the degree of roundness of the grains. The roundness varies from 0.23 to 0.39, but is in the range of 0.26 to 0.36 for most samples. These values are acceptable for most industrial sand uses, although well below the 0.6 or better required for proppant sands.

Mineral Composition

The mineral composition of these eolian sands is quite variable (Table 2). Based on grain counts of 100 grains, quartz contents vary from 63 to 98 percent, feldspar from 4 to 16 percent, chert from 0 to 7 percent, and rock fragments from 0 to 8 percent. A trace of mica was observed in 5 samples. Samples 17 and 18 from one dune in the Clearwater River valley are extraordinarily high in quartz content, as is sample 27 from an upland dune nearby. The heavy mineral contents range widely from 0.4 to 1.2 percent (of the modal fraction), which is substantially higher than in the other sands considered in this study. Exceptions are samples 17 and 18, with only slightly more than 0.1 percent heavy minerals. The most common heavies were identified as tourmaline, zircon, and chloritoid. The clay minerals were identified as illite, kaolinite, chlorite and montmorillonite, with illite being the predominant clay in all samples.

Iron staining on the surfaces of quartz grains is a relatively pronounced feature of these eolian sands. A measure of the degree of iron staining is given in table 2, based on 100-grain counts and visual estimates as described previously. The least amount of staining is seen on samples 17 and 18, 23 and 27. In these samples as much as 50 percent of the grains are clear and the staining observed is mainly of light to medium category — similar to sands previously described. However the remaining eolian sand samples all have significantly higher proportions of stained grains in the medium to heavy category.

Chemical Composition

Chemical compositions of the unwashed eolian bulk sands and the washed modal fractions are reported in table 3. Wide variations in the compositions are indicated. In the unwashed bulk sands, silica values range from 84 to 98 percent, alumina from 1 to 6 percent, and iron (expressed as Fe_2O_3) from 0.1 to 1.7 percent. The alumina content is due largely to the presence of feldspar, and varies inversely with the silica content. Iron oxide content is a function of both the degree of iron staining and the contents of heavy and magnetic minerals (Table 2). Titania, the other main contaminant of the sands, varies in a similar manner but within a much smaller range, from less than 0.1 to about 0.3 percent. With washing and screening to the modal size fraction, iron and titania are both reduced by one-quarter to one-third; the alumina content is not significantly changed.

Within the study area, the compositional variations in these eolian sands follow a general pattern of improvement in silica quality northeastward. The lowest quality sands are samples 19, 20, and 21 from the Thickwood Hills area west of Fort McMurray. These are similar to low grade dune sands tested from areas in central and southern Alberta (Carrigy, 1970; Holter, 1971, 1972), and even with beneficiation cannot be raised sufficiently in quality to be classed as silica sand. However, the other dune sands tested in the study area are much superior in quality. The general northeastward improvement culminates in samples 17 and 18, which are unusually pure for dune sands and quite unlike any investigated previously in Alberta. These samples, from a dune in the Clearwater River valley, compare favorably with any of the sands investigated in this study. Silica contents are about 98 percent and iron oxide is just slightly above 0.1 percent in unwashed bulk samples.

BENEFICIATION

Beneficiation studies were not performed on all dune samples. Only the samples from the Clearwater River valley dune (17 and 18) and samples 22, 23, and 27 were considered high enough in silica quality to warrant further upgrading treatment. As in the sands discussed previously, iron is the critical contaminant, and the tests were directed primarily toward lowering the iron content.

Outline of Tests Performed

The beneficiation procedures followed are as outlined in figure 5. A summary of results of the tests performed on the modal size of the samples is given in table 9.

Washing and Sieving

With washing and sieving, the modal fractions exhibit significantly lower iron contents. Best results were obtained for samples 17 and 18, with 0.10 and 0.09 percent Fe_2O_3 respectively.

Magnetic and Heavy Liquid Separation

Iron content was further reduced with magnetic separation of the washed, sieved modal fractions using a Franz isodynamic separator set at 1.7 amperes of current, 18 degrees slope, and

Table 9.   Progressive Effects of Beneficiation Treatments on Eolian Sands

Sample Number	Sample Condition*	Constituent (Wt. %)			
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2
17	Unwashed	97.85	0.94	0.14	0.08
	Washed and sieved (modal fraction)	98.16	0.87	0.10	0.07
	Minerals removed**				
	Light fraction (heavy removed)	98.18	0.91	0.11	0.06
	Nonmagnetic fraction (magnetic removed)	98.06	0.81	0.06	0.06
	Treated with HCl acid				
	Light fraction	98.33	0.80	0.10	0.06
	Nonmagnetic fraction	98.10	0.56	0.04	0.05
18	Unwashed	98.13	0.94	0.12	0.09
	Washed and sieved (modal fraction)	98.25	0.91	0.09	0.06
	Minerals removed**				
	Light fraction (heavy removed)	98.24	0.95	0.09	0.06
	Nonmagnetic fraction (magnetic removed)	98.37	0.86	0.05	-
	Treated with HCl acid				
	Light fraction	98.24	0.87	0.09	0.02
	Nonmagnetic fraction	-	0.53	0.05	-
22	Unwashed	95.27	1.81	0.58	0.11
	Washed and sieved (modal fraction)	95.83	0.70	0.47	0.05
	Minerals removed**				
	Light fraction (heavy removed)	96.96	1.68	0.25	0.09
	Nonmagnetic fraction (magnetic removed)	-	-	-	-
	Treated with HCl acid				
	Light fraction	-	-	-	-
	Nonmagnetic fraction	-	-	-	-
23	Unwashed	95.42	1.91	0.49	0.09
	Washed and sieved (modal fraction)	96.33	1.84	0.33	0.07
	Minerals removed**				
	Light fraction (heavy removed)	96.42	1.67	0.30	0.05
	Nonmagnetic fraction (magnetic removed)	-	-	-	-
	Treated with HCl acid				
	Light fraction	-	-	-	-
	Nonmagnetic fraction (magnetic removed)	-	-	-	-
27	Unwashed	96.11	1.64	0.49	0.08
	Washed and sieved (modal fraction)	97.05	1.53	0.28	0.07
	Minerals removed**				
	Light fraction (heavy removed)	97.23	1.36	0.17	0.07
	Nonmagnetic fraction (magnetic removed)	97.37	0.91	0.13	-
	Treated with HCl acid				
	Light fraction	-	-	-	-
	Nonmagnetic fraction (magnetic removed)	-	-	-	-

* See figure 5 for a flow diagram of beneficiation procedure.

** The modal fraction was split into two parts: one portion was subjected to heavy mineral separation, and the other portion was subjected to magnetic mineral separation.

10 degrees tilt. In samples 17 and 18 the iron content was lowered to 0.06 and 0.05 percent Fe_2O_3. Sample 27 went from 0.28 down to 0.13 percent Fe_2O_3. Samples 22 and 23 were not tested. The magnetic minerals identified were quartz and feldspar grains containing inclusions, garnet, staurolite, tourmaline, and hematite. Table 3 gives the weight percent of magnetic minerals removed from the modal fractions at different magnetic intensities.

Heavy liquid separations performed on separate washed, sieved modal size fractions produced virtually no change except in sample 27. In that sample the iron content decreased from 0.28 to 0.17 percent Fe_2O_3.

Acid Leach

The nonmagnetic fraction of samples 17 and 18 was boiled in 1 percent HCl for 10 minutes. This treatment lowered the iron content in sample 17 from 0.06 to 0.04 percent Fe_2O_3. The iron content of sample 18 was unaffected.

Summary of Results

Sands of the dune in the Clearwater River valley are of high quality and compare favorably with the sands of other sources investigated. Silica, alumina, and titania values are similar, iron content is as low or lower, and muscovite is absent. From the particle size point of view, the sands of this dune are more suitable than the tailings sands for the manufacture of most kinds of glasses. In the other dune sands tested, the iron content was not lowered quite sufficiently for glass grade requirements.

SUMMARY

A summary of the results of the study is given in table 10. The sands are presented in the table approximately in order of their glassmaking potential.

1. *Oil sand tailings* are considered to be one of the main potential sources of silica sand in the central and northern part of the province. These sands are high in silica (95 to 98 percent SiO_2 in the raw sample), and are readily available in unlimited quantities. Although some upgrading is required, the sands seem to respond well to conventional beneficiation techniques.

The main contaminants of the oil sand tailings are the residual oil, the iron content, the "fines," and the mica. Removal of residual oil from the grains can be accomplished by scrubbing or burning. The "fines" can be removed by screening or by commercial desliming techniques. Beneficiation tests indicate that the iron content can be lowered from 0.18 percent Fe_2O_3 to 0.08 percent by washing and sieving, to 0.05 percent by magnetic separation, and finally to 0.02 percent Fe_2O_3 by acid leach — an iron content well within range for high quality glass manufacture. The mica can be removed by flotation (Appendix C), or may even come off with desliming. However, the

quantity of mica remaining in the sand tailings after oil sand processing is practically too small to measure and may not have to be removed at all.

There should be few constraints on the exploitation of this otherwise wasted "by-product" of oil sand production. It is anticipated that the cost of making the oil sand tailings available to a sand purification plant would be low or practically nil, requiring only simple negotiation between producer and operator. The recovery of the sands would, of course, have to be coordinated with the mining operation. The fact that little or no mining costs would be incurred, and the availability of unlimited quantities of this sand, should more than offset the costs of beneficiation.

Overall, the oil sand tailings are potentially a very good source of silica sand suitable for many uses, including glass-making, but not including use as proppant sand in hydraulic fracturing. For this use, the roundness factor of the grain shapes falls far below the specified requirements.

2. A second potential source of silica sand within easy reach of Fort McMurray is the *alluvial sands* from the buried bedrock channel in the Clearwater River valley. The silica-rich sands (95 to 97 percent SiO_2 in the raw sand), are well sorted and within the specified grain size range for glass and fiber glass manufacture, and are amenable to beneficiation. Grain roundness values are acceptable for most industrial sand uses but are well below the requirement for proppant sands.

The main contaminant of the alluvial sands is iron. Results of beneficiation tests indicate that (by simple washing and sieving, magnetic separation, and acid leaching) the iron-content can be lowered from 0.3 percent Fe_2O_3 to 0.02 percent. This is well within the limits specified for good quality glass manufacture.

Indications are that the deposit is of considerable size. Testholes drilled at Fort McMurray penetrated a 100-foot deep (30-m) sand-filled channel. Testhole drilling 35 miles (56 km) up the Clearwater River has also indicated the presence of a channel 142 feet (43 m) deep, largely filled with clean white sand. Although no data exists for the area between these sites, it is probable that a continuous bedrock channel 100 to 140 feet (30 to 43 m) deep underlies the Clearwater River valley.

Exploitation of this source of silica sand would require a dredging operation, as the channel deposits are below the river level. This is a mining method commonly used to recover silica sands. Access and transportation would present few problems as the deposit is located within and adjacent to Fort McMurray. This deposit could also prove to be a valuable source of industrial or construction sand.

In some respects the alluvial sands are superior to the tailings. The grain size distribution is better, approaching more closely

Table 10. Summary of Results with Conclusions

Source	Grade Beneficiated		Main Contaminants	Beneficiation	Accessibility	Exploitability
	SiO_2	Fe_2O_3				
Oil sand tailings	98-99	0.02-0.04	iron, residual oil, film, fines, mica	acid leach, scrubbing or burning, screening, flotation, tabling or electrostatic separation	no constraints - excellent road access to plant site	no constraints - utilization of otherwise wasted by-product; unlimited quantity available
Alluvial bedrock channel sands	97-98	0.02-0.05	iron	acid leach[1]	no constraints - easy access to deposits; close to Fort McMurray	may be environmental constraints on mining below river level in channel deposits; dredging operation likely; unlimited quantity
Eolian sands	95-98	0.02-0.1	iron, alumina	acid leach (not practical for most sands - too low grade)	variable - some dunes located close to roads, others 40 to 50 miles from Fort McMurray up Clearwater River valley; no road access	no constraints - surface deposits with no overburden; quantities locally limited
McMurray Formation sands (unimpregnated)	97-98	0.01-0.02	mica, iron	acid leach, flotation, tabling, or electrostatic separation[2]	difficult - 20 to 50 miles from Fort McMurray up Clearwater River valley; no road access	uncertain - bedrock deposit with thick overburden in many localities; further exploration needed to delineate best locations for mining

[1] Acid leach gave the best results in beneficiation trials to achieve optimum iron removal.

[2] Additional beneficiation studies are proposed in this area to determine the most effective technique.

the desirable size range for glass manufacture: Also, mica is not present. However, the alluvial sands do lack the "availability" of the oil sand tailings, and environmental restrictions could be imposed on mining.

3. Some of the *eolian sands* sampled compared favorably with the sands of other sources investigated. Most are well-sorted, medium- to fine-grained sands of generally better quality than dune sands from other parts of the province. In any one area, the quantity of material available is usually limited. As dune sands are surface deposits there is usually very little overburden.

One dune situated in the Clearwater River valley near the Saskatchewan border is of very high quality, with a silica content of 98 percent in the beneficiated product. Iron is the critical contaminant. This was reduced in beneficiation tests from 0.12 percent Fe_2O_3 to 0.09 percent by washing and sieving, and to 0.05 percent Fe_2O_3 by magnetic separation. However, this deposit is situated 40 to 50 miles (64 to 80 km) east from Fort McMurray up the Clearwater River valley, with no road access, so that its remarkable purity is of somewhat academic interest.

Some dune deposits of lesser quality situated closer to Fort McMurray in the Thickwood Hills were also examined. They are typical of low-grade dune sands tested from other areas in central and southern Alberta, and even with beneficiation these sands cannot be improved sufficiently in quality to be classed as silica sand. On the other hand, because of their proximity to Fort McMurray and areas of future oil sands development they could well be considered a source of industrial and constructional sand.

4. The *McMurray Formation sands* samples in this study are fairly pure, with silica contents of 97 to 98 percent SiO_2 after beneficiation. The sands also have desirable textural properties, being well-sorted, and medium- to fine-grained. The major disadvantage is that these sands are highly

micaceous. Grain roundness values are acceptable for most industrial sand uses but are well below what is required for proppant sands.

The main contaminants are iron and mica. Beneficiation tests were directed towards reducing the iron content. Washing and sieving lowered iron contents from 0.2 percent Fe_2O_3 to 0.08 percent. Magnetic separation or heavy liquid separation further reduced the iron content to 0.06 percent and acid leaching reduced this to 0.02 percent Fe_2O_3 — an acceptable level for glass manufacture. However, it would be necessary to remove the excessive amounts of mica present.

Exploitability of the deposit is uncertain. Because this is a bedrock deposit with thick overburden in many localities, further exploration would be needed to delineate localities suitable for quarrying. Access would be difficult, as the bitumen-free sandstones are 20 to 50 miles (32 to 80 km) up the Clearwater River valley without road access. The disadvantages outlined mean that the McMurray Formation sandstones must be discounted as a potential source of silica sand.

CONCLUSIONS

Silica sands from the Fort McMurray area compare favorably in quality with silica sands supplied to Alberta markets today, or in the past, and with sands from sources possibly to be developed in the future (Fig. 2). The main hindrance to the development of this resource is Fort McMurray's remoteness from glass plants presently operating in Alberta. Furthermore, it is unlikely that a glass plant will be established in Fort McMurray because of this remoteness, and consequent distance from markets. However, at present, freight costs between Fort McMurray and Edmonton are competitive with freight costs between Edmonton and Selkirk, Manitoba, the largest current supplier. Therefore, if and when it becomes feasible for the glass industry to expand into the northern or central part of the province, these sands in the Fort McMurray area must be seriously considered as alternative sources of silica sand.

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APPENDIX A

GLASS SAND SPECIFICATIONS

Silica sand is the principal raw material used by the glass industry, forming over 70 percent of the raw material mix. For this use it is commonly referred to as glass sand, and is evaluated as follows:

(1) The sand must be 99 to 100 percent SiO_2, and free of contaminants which discolor the glass. Iron[8] is the most serious contaminant, and the amount that can be tolerated is very small and varies with the end products. Permissible iron content is lowest for optical glass where it should not exceed 0.009 percent Fe_2O_3. For glass containers, iron content must be less than 0.04 percent, but for fiber glass insulation manufacture, as much as 0.4 percent Fe_2O_3 can be tolerated.

Titania (titanium dioxide) is also a colorant, but is less troublesome than iron. Small amounts of alumina are acceptable in the form of feldspar; however, it must be uniformly distributed.

Lime, magnesia and other alkalis are generally also to be avoided, but may be acceptable if maintained at a consistent level. Typical chemical specifications for various glass products are given in table 11.

(2) Highly refractory minerals such as zircon, spinel, kyanite, or sillimanite are detrimental because they survive in the melt, giving rise to unsightly "stones" in the product. Mica also is objectionable as it may cause specks and blow holes in the glass (Lilge, 1945).

(3) Uniform grain size is important. Grain size distribution of the sand particles largely controls the success of the melting process. Coarse grains take longer to melt; fine grains may find their way to the top of the batch and remain unaffected by the rest of the melt. Glassmakers generally prefer a narrow size range, preferably $-30 + 100$ mesh sizes (0.6 to 0.15 mm). However, finer sizes are acceptable for fiberglass manufacture. Also, glass manufacturers, concerned with energy costs, are beginning to consider using finer size ranges, as melting finer sands requires less energy than melting coarser sands (Edwards and Copley, 1977). The composition for glass sand as specified by two Alberta glass manufacturers is given in table 12.

Specifications for the many other uses of silica sand have been discussed by McLaws (1971) and are not included in this report.

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[8]Glassmakers that use electrically heated furnaces are beginning to look for sands with lower iron (Fe_2O_3) contamination (less than 0.025 percent) as iron in the glass sand in the melt renders it opaque to infrared radiation and reduces the thermal efficiency of the furnaces.

Table 11.   Chemical Specifications of Glass Sands for Various Glass Products

Use	Constituent (Wt. %)			
	SiO_2 (min)	Fe_2O_3 (max)	Al_2O_3 (max)	TiO_2 (max)
Optical glass	99+	0.008	0.1	–
Plate	99+	0.027	0.20	0.02
Colorless container	99+	0.042	0.05	0.05
Colored glass	99+	0.15	0.05	0.10
Fiber glass insulation	93	0.4	2.5	0.10

Table 12.   Specifications of Glassmakers in Alberta

Company	Constituent (Wt. %)			
	SiO_2 (min)	Fe_2O_3 (max)	Al_2O_3 (max)	TiO_2 (max)
Dominion Glass[1]				
Colorless container	99 ± 0.4	0.042	0.05	0.05
Colored glass	99 ± 0.4	0.15	0.05	0.10
Fiberglas Canada[2]				
Fiber glass insulation	92.4	0.2-0.4	2.5	0.1

[1] Grain size: -40+100
[2] Grain size: -50+140

APPENDIX B

LABORATORY PROCEDURES FOR
EVALUATION OF SANDS AS
POTENTIAL SOURCES OF SILICA SAND

INTRODUCTION

Pure silica sands and sandstones are rare. Most contain impurities such as clays, feldspars, micas, "heavy minerals," iron-stained grains, and grains with inclusions of iron minerals. Conventional practice in processing silica sands can involve such elaborate treatment as high-density attrition scrubbing and stage washing or acid leaching or both, to remove surficial impurities, and froth flotation, magnetic separation or high-tension electrostatic separation to remove remaining impurities. For example, Indusmin Limited, the largest producer of high-quality silica sand in Canada, mines and processes the Potsdam sandstone at St. Canut, Quebec and employs a three-stage beneficiation program after the sand is crushed and screened to −20+150 mesh. This program includes attrition scrubbing and desliming, flotation, and high-intensity magnetic separation.

Before any attempt can be made to determine the economic feasibility of utilizing a silica sand deposit, a detailed mineralogical and chemical study of the deposit must be completed. If the distribution and form of the impurities are known it is possible to predict which method of treatment is likely to yield the best results. An example of this would be a sand in which most of the iron content is present as a film on the surface of the quartz grains; this type of sand would call for scrubbing and possibly acid leaching, but concentration methods are not indicated. By contrast, a sand free from iron and clay coatings, but containing significant amounts of free mineral impurities would require treatment by concentration techniques, the choice of the treatment used depending on the minerals present in the sand. If the minerals are predominantly ferromagnetic, treatment may simply consist of magnetic separation; but if there is a varied suite of minerals it may be necessary to use either gravity concentration or flotation methods (Taggart, 1945).

In the selection of a beneficiation method, use can be made of differences in particle size, density, magnetic susceptibilities, and electrical characteristics. Two major differences which allow separations to be made commercially are specific gravity and magnetic susceptibility.[9] To remove surface

coatings of iron and other impurities from the grains of sand, it is often necessary to use acid or alkali treatment. Acid wash is a common mineral dressing technique (Taggart, 1945, p. 11-78).

For this study, beneficiation tests included magnetic and heavy liquid separations, and acid leach. Tests were "bench scale," preliminary in nature, and intended only to show the major differences which would allow separations to be made between the quartz and other minerals present. Tests were also conducted to determine to what extent the surface impurities could be removed.

The procedure followed in evaluating the sands is illustrated on the flow chart (Fig. 5) and discussed below.

SAMPLE PREPARATION

All samples were dried, weighed, and split into portions for testing and storage by using a Jones sample splitter. Samples were washed in water with a conditioner (Calgon). Oil sand tailings samples were boiled in toluene to dissolve out the oil residue before washing in water (also using a conditioner and "wetting agent" Calgon).

PARTICLE-SIZE DISTRIBUTION

The particle size distribution was determined by decanting the clay-size material and then passing the sand fraction through a nest of U.S. Standard sieves according to the procedures set out by the American Society for Testing and Materials (ASTM designation C429-65). The results of the mechanical analyses[10] are tabulated in table 1 and displayed graphically in figures 7, 10, 15, and 17.

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[9]Examples of the principles involved in separation by specific gravity and magnetic separations would be: the mineral zircon (SG 4.6) sinks in a heavy liquid media (tetrabromo ethane, SG 2.9), in which quartz (SG 2.6) rises; magnetite, which is highly permeable to magnetic force will move towards a field of concentrated magnetic force; on the other hand, the force will have little effect on the motion of a quartz grain unless heavily coated with iron oxide, or with iron inclusions.

[10]Sand particles are classified on a size basis, and the concept of size is usually considered in terms of the diameter. In practice, size is measured in terms of the least cross-sectional area of the particles because they are tested on a screen having definite mesh openings through which the particle will pass or on which it will be retained. The size is a continuous variable and an infinite number of screens would be needed for a complete analysis. This is impractical, so the particles are grouped into openings. Standard screens are made with definite relationships between succeeding screens. The Tyler and U.S. Standard ratio is $\sqrt{2}$ so that each screen opening is twice the area of the following. Numbers are given to size ranges. Material is described as being in the size range 140 to 200 mesh meaning the diameters of the material falls between 0.105 and 0.074 mm. The *modal size fraction* is the *size range* in which the greatest weight percent of sand particles with approximately the same diameters occurs.

MINERALOGICAL COMPOSITION

The mineralogical composition was determined by means of a grain count of 100 grains in each fraction. These counts were then weighted and combined to give the approximate mineral compositions of the whole sample. Results are given in table 2 along with the mineral compositions of the modal fractions. The clay-size materials (-5μ) were identified using X-ray diffraction techniques. Heavy minerals[11] — those which sink in tetrabromo ethane with a specific gravity of 2.95 — were separated by a sink-float process. The opaque heavy mineral grains were identified by stereomicroscopic technique and X-ray diffraction analyses, and the nonopaque minerals by observation under the petrographic microscope. The percentage of heavy minerals in each sample is given in table 2.

GRAIN SHAPE

Grain shape involves two factors: sphericity[12] and roundness.[13] In these sands, which consist mainly of the mineral quartz, sphericity showed little variation from a medium value, and so grain shape in this study is expressed mainly in terms of roundness. Roundness is an important property in the evaluation of silica sands for certain uses; for example, proppant sands used in hydraulic fracturing require a roundness factor of 0.6 or better.

The most common method of determining grain roundness is by visual comparison of grain shapes with standard roundness images. These images are of grain shapes representing varying degrees of roundness, which are grouped into categories and expressed as numerical limits within the roundess scale of 0 to 1. For this study a four-fold breakdown of the scale was used, in which the shapes that could be described as "angular" fall in the range of 0 to 0.25, "subangular" 0.25 to 0.50, "subround" 0.50 to 0.75, and "round" 0.75 to 1. The shape of individual grains is estimated visually under the stereomicroscope from comparison with the standard images. To determine the average roundness for

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[11]In sand accumulation, particles of a certain size and specific gravity will be concentrated along with particles of smaller size but greater specific gravity. The heavy minerals are nearly always found in the finer grains of sand (−100 or −140 mesh), and often practically absent from the coarser grades. The heavy-mineral contents are often rich in iron and are therefore a contributor to the iron impurity in potential glass sands.

[12]Sphericity is a function of how nearly equal the three dimensions of a particle are, that is, the degree to which the particle shape approaches that of a sphere.

[13]Roundness is a function of how rounded off the corners and edges of a particle are. It is defined as the ratio of the average radius of curvatures of all corners to the radius of the largest inscribed circle (Wadell, 1932). On the Wadell scale, roundness is expressed as some numerical value between 0 and 1: a perfectly rounded particle such as a sphere of a cylinder capped with two hemispheres has a value of 1; less rounded particles have values of less than 1.

all the grains, a standard grain count method (100 grains) was employed. The median numerical value was assumed for the grains assigned to each roundness category, and the average value was then computed by the method of moments. These roundness data are presented in table 1 as numbers followed by the letter r.

SURFACE STAINING AND INCLUSIONS

In order to determine the manner in which the iron content is distributed, surface iron staining was estimated and inclusions in the grains noted. Sands observed at surface exposures often have a tan or yellow coating on the grain surfaces, usually due to a thin film of iron oxide. In addition, some of the quartz grains contain small opaque inclusions that probably form a small part of the iron content of the samples. Surface staining of 100 sand-size grains in each sample was estimated visually under a stereomicroscope and each grain was assigned to one of four categories: heavy, medium, or light staining, and clear depending upon the nature of the staining. If the stain covered less than half the grain surface in a thin, spotty or patchy manner it was termed light. If the stain covered more than half the surface in a more or less continuous coating but still left the quartz grain transparent, it was classed as medium. Staining of such intensity as to render the grain opaque or translucent over half or more of its surface was classified as heavy. Grains with inclusions but no staining were counted separately. The results of the examination of staining on the grains and inclusions in the grains are given in table 2.

CHEMICAL COMPOSITION

Standard laboratory procedures were used to chemically analyze raw bulk samples, washed modal and glass size fractions, and all beneficiated sand fractions. The results of the analyses are given in tables 3, 4, 5, 7, 8, and 9.

BENEFICIATION

All of the sands sampled contained undesirable quantities of iron, clay, heavy minerals, or mica. Different beneficiation processes were tried to determine suitable methods for removing impurities and upgrading the sands to glass sand quality. No attempt was made to determine which method was most economical. Most of the beneficiation effort in this study has been directed towards reducing the iron content, which at the same time reduces the titania and alumina. The procedures followed (summarized in Fig. 5) were:

(1) washing in water with a conditioner (Calgon) to remove iron coatings and clay;

(2) sieving to modal size or glass sand size (−30+100 mesh) or both which at the same time removes the majority of the heavy minerals which are more abundant in the finer fractions;

(3) heavy liquid separation to remove heavy minerals; or

(4) magnetic separation to remove the free magnetic particles, grains heavily coated with iron oxide, and grains with magnetic inclusions;

(5) leaching with acid to remove the iron oxide staining and at the same time possibly dissolving the smaller discrete particles of iron and titanium minerals.

WASHING AND SIEVING

All samples were washed and screened. Tests were performed on modal size fractions. Oil sand tailings were screened to glass sand size (−30+100 mesh) and tests were also performed on this fraction.

HEAVY LIQUID SEPARATION

Heavy liquid separations were performed on modal size fractions, and on glass sand size fractions of tailings sands. The weight percentages of heavy minerals in the modal and glass sand size fractions are given in table 2. The light fractions were analyzed to determine chemical compositions (Tables 3 and 4).

MAGNETIC SEPARATION

Magnetic separations were performed at various magnetic intensities with a Franz isodynamic separator set at slope 18 degrees and tilt 10 degrees. Cumulative weight percentages of minerals removed at various magnetic field intensities (0.1, 0.9, and 1.7 amperes of current) are given in table 2. Chemical analyses were made of the nonmagnetic fractions (Tables 3 and 4).

ACID LEACH

In the acid leach trials, samples were boiled in 1 percent hydrochloric acid (HCl) for 10 minutes. To determine the maximum possible reduction of iron using this method, samples were boiled in 1 percent hydrofluoric (HF) acid for 2 hours. Chemical analyses were done after each test and results given in tables 5, 7, 8, and 9.

FLOTATION TRIALS

Flotation tests to remove mica were performed on a GCOS plant 3 tailings sand sample using a laboratory flotation cell and standard reagents for conditioning and frothing. The test was partially successful. Further tests to remove mica were performed by a testing laboratory; results are reported in Appendix C.

APPENDIX C

RESULTS OF PRELIMINARY BENEFICIATION TESTS BY LAKEFIELD RESEARCH
OF CANADA LIMITED ON OIL SAND TAILINGS

At the request of Alberta Research Council, Lakefield Research of Canada Limited, Lakefield, Ontario, carried out tests on a sample of GCOS oil sand tailings to determine its amenability to upgrading (by standard industrial practices) to glass sand quality. Tests were performed to remove residual oil, fines, and mica, and to reduce iron content to 0.05 percent or less Fe_2O_3 in the -28+100 mesh size range. Five separate tests were performed. Visual examination and chemical analyses for Fe_2O_3 were used to interpret the results. Details of some of the tests are reported here.

TEST NO. 1

In this test the tailings sand sample was separated into three size fractions (+28 mesh, -28+100, -100 mesh) and the middle fraction was subjected to high density scrubbing, desliming, flotation, and leaching with HCl to remove residual iron. The size distribution of the head sample was as follows:

Mesh Size (Tyler)	Wt. % Retained Individual	Wt. % Passing Cumulative
+28	1.9	98.1
-28+100	78.0	20.1
-100	20.1	-
Total	100.0	

Mechanical analysis indicated that 78 percent by weight of the sample was in the -28+100 mesh size range, and consisted of many grains cemented in aggregates, solid black hydrocarbon particles, brown stained grains, opalescent grains, and mica in consolidated "books." The +28 mesh consisted of rock chips up to 1/4 inch in diameter, and also contained black, soft particles of some hydrocarbon compound.

Scrubbing

A 1000 gm sample of -28+100 mesh size was scrubbed in water at 74 percent solids in a Wemco scrubber for 20 minutes at 1250 RPM. The temperature increased from 15°C to 52°C. The pulp

was deslimed four times by decantation until no mica was visible at the surface. Results of scrubbing[14] and desliming are given below:

Products	Wt. %		Assay % Fe_2O_3	% Fe_2O_3 Distribution Individual
	Individual	Overall		
Sand	95.8	74.7	0.082	64.0
Slime	4.2	3.3	1.05	36.0
Head (-28+100)	100.0	78.0	0.12	100.0

Flotation

A 500 gm sample of deslimed sand was placed in an Agitair flotation cell, the pH adjusted to pH 6 with 1.04 lb/ton H_2SO_4, and a mica flotation performed using 0.02 lb/ton of dehydroabietylamine and 0.1 lb/ton of petroleum sulfonate. The pH was then adjusted to pH 3 by adding HF and a further flotation performed to remove other contaminants such as feldspar and iron minerals.

Results were as follows:

Products	Wt. %		Assay % Fe_2O_3	% Fe_2O_3 Distribution Individual
	Individual	Overall		
Froth	2.67	2.0	1.30	30.0
Cell	97.35	72.7	0.059	70.0
Head	100.0	74.7	0.082	100.0

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[14] It was not determined whether the residual oil was affected by scrubbing with water.

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Acid Leaching

A 455 gm sample of the above cell product was acid leached using 100 g/l HCl at 80°C temperature with 65 percent solids. The results are as follows:

Product	Amount	% Fe_2O_3
Leach solution	125 ml	0.297 g/l
Wash solution	418 ml	0.125 g/l
Leach product	451.8 g	0.040%
Flotation product	455.0 g	0.059%

The leach product appeared light in color, although discolored and stained grains were still visible. It was not possible to detect mica under the binocular microscope.

Summary of Test No. 1 Results

The following flowchart shows iron reduction with each successive step.

Flowchart of Test No. 1 Results Showing Iron Reduction

% Fe_2O_3

Oil Sand	-
Screening → +28-100 mesh	0.12
Scrubbing and Desliming	0.082
Flotation	0.059
Acid Leaching	0.040
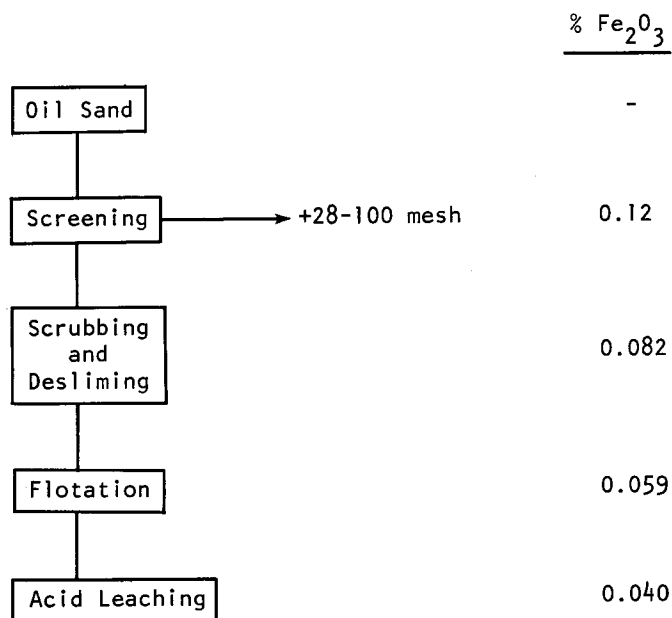
TEST NO. 2

Test 2 involved scrubbing the -28 mesh raw sand in water and desliming (without screening out the -100 mesh fraction) to remove some of the fines, followed by flotation. With the -100 mesh fraction present the flotation was less selective, and a heavy froth product was obtained. Both products were then screened and the +100 mesh portions combined. A scavenger flotation stage was introduced to complete the flotation. Results of flotation were:

Product	Wt %		% Fe$_2$O$_3$	% Fe$_2$O$_3$ Distribution
	Individual	Overall	% Fe$_2$O$_3$	Distribution
Scavenger cell product	51.4	41.5	0.068	34.2
Scavenger froth product	25.4	20.5	0.108	36.9
Rougher cell -100 mesh	0.2	0.2	0.79	1.9
Rougher froth -100 mesh	23.0	18.5	0.166	37.0
Head	100.0	80.7	0.102	100.0

The final cell product was split into three lots for leaching with the following conditions:

	2-1	2-2	2-3
Leaching Time, minutes	30	30	30
Pulp density, %	65	65	65
Temperature, °C	18	67	67
Acid strength, g/l HCl	100	100	50

Test No. 2-1

Product	Amount	Assay % Fe$_2$O$_3$	% Fe$_2$O$_3$ Distribution
Leach solution	182 ml	0.246 g/l	20.0
Wash solution	264 ml	0.054 g/l	6.0
Leach residue	324.5 g	0.051%	74.0
Head	328 g	0.068%	100.0

Test No. 2-2

Product	Amount	Assay % Fe_2O_3	% Fe_2O_3 Distribution
Leach solution	134 ml	0.355 g/l	22.1
Wash solution	414 ml	0.043 g/l	8.8
Leach residue	323.5 g	0.046%	69.0
Head	328 g	0.066%	100.0

Test 2-3

Product	Amount	Assay % Fe_2O_3	% Fe_2O_3 Distribution
Leach solution	142 ml	0.346 g/l	22.1
Wash solution	206 ml	0.166 g/l	15.3
Leach residue	322.1 g	0.043%	62.6

Results of test 2 are summarized in the flowchart which shows the reduction of iron with each step of the test. This test indicated that flotation was less effective when the -100 mesh fines were present. Acid leaching removed about 30 percent of the Fe_2O_3. The leaching tests indicated that temperature was more important than acid strength.

TEST NO. 3

In test 3 the sample was scrubbed in the presence of Na_2SiO_3 and NaOH to remove oil residue films,[15] and then subjected to flotation and leaching.

Scrubbing

A 1 kg sample of -28 mesh tailings was scrubbed for 20 minutes at 80 percent solids with 5 lb/ton Na_2SiO_3 and 2 lb/ton NaOH. The temperature rose from 21°C to 37°C. After desliming, the -100 mesh portion was removed by screening. Approximately 68 percent of the feed was recovered as a sand fraction containing 0.082 percent Fe_2O_3.

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[15]No quantitative extraction tests were performed to evaluate the effectiveness of these reagents for removal of residual oil.

Flowchart of Test No. 2 Results Showing Iron Reduction

		Overall Weight %	Iron Content Fe$_2$O$_3$ %
Oil sand		100.0	0.12
Screening	+28 mesh	2.0	
Scrubbing	3 stages		
Desliming	Slime	17.3	
Sand	Reserve	80.7	0.102
Flotation			
Froth screen — 100 mesh — Cell screen	-100 mesh cell	0.2	0.79
	-100 mesh froth	18.5	0.166
Scavenge	Froth	20.5	0.108
Cell product		41.5	0.068
HCl leaching			0.043

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Product	Wt. %
+28 mesh	2.7
-28+100 mesh	68.4
-100 (slime) mesh	28.9
Head	100.0

Flotation

The pH was adjusted to 3 with 10 lb/ton HF and 9 lb/ton H_2SO_4. Froth products were removed with 0.5 lb/ton dehydroabietylamine and 0.07 lb/ton polyglycal type frother over a 15 minute period. After flotation the cell product assayed 0.043 percent Fe_2O_3, and only 2.7 percent by weight of the flotation feed was removed as a froth waste product.

Product	Wt. % Individual	Overall	Assay % Fe_2O_3	% Fe_2O_3 Distribution
Cell product	97.3	66.5	0.043	51.0
Froth product	2.7	1.8	1.50	49.0
Head (-28+100)	100.0	68.4	0.082	100.0

Leaching

A sample of the above cell product (0.043 percent Fe_2O_3) was leached for 30 minutes at 70°C in 100 g/l HCl. Iron content was further reduced to 0.036 percent Fe_2O_3. Overall weight recovery was 66 percent. Results are as follows:

Product	Amount	Assay % Fe_2O_3	% Fe_2O_3 Distribution
Leach solution	227 ml	0.105 g/l	8.6
Wash solution	713 ml	0.030 g/l	7.5
Leach residue	660 g	0.036%	83.9
Head (cell product)	665.7 g	0.043%	100.0

Summary of Test No. 3 Results

The following is a flowchart indicating iron reduction with each successive step in test 3.

Flowchart Summary of Test No. 3 Results Showing Iron Reduction

	Iron Reduction % Fe_2O_3
Oil Sand	-
Screening ────→ +28 mesh	-
Scrubbing	-
Desliming	-
Screening ────→ -100 mesh	0.12
Sand	0.082
Flotation	0.043
Acid Leaching	0.036

Flotation and acid leaching gave a low-iron product satisfactory for glass sand. High acid requirements for the flotation resulted from the $NaOH-Na_2SiO_3$ scrubbing.

TEST NO. 4

Test 4 was essentially a repeat of test 3 but without the caustic. However, the iron content of the flotation product was higher (0.063 percent Fe_2O_3 and after the acid leaching, 0.055 percent Fe_2O_3), possibly as a result of contamination.

TEST NO. 5

In test 4 a 25 mm cyclone (Krebs PC-1-832, Vortex diameter 9 mm, Apex diameter 3 mm) was used for classification at 100 mesh, using sand scrubbed in water only. The +48 mesh fraction was removed to prevent plugging of the fine apex opening. Two passes were made: at 10 psig (1st pass), and 15 psig (2nd pass) with the following results:

Product	g	Wt. %	+100 Mesh (%)	-100 Mesh (%)
1st pass overflow	108	10.3	56.5	43.5
2nd pass overflow	55	5.2	46.3	53.7
2nd pass underflow	710	71.0	97.3	2.7
2nd pass remainder	135	13.5	75.7	24.3
Head	1008	100.0		

The cyclone separation recovered 71 percent of the feed sand with only 2.7 percent of -100 mesh size material contained. By combining the +48 mesh portion of the sample with the 2nd pass underflow, the yield would be 73.9 percent of the 80.7 percent of deslimed feed (see flowchart test 2), or 59.6 percent of original tailing sample.

The final sand fraction from the cyclone classification and the +48 mesh portion of the sample subsequently were combined for flotation and acid leaching. Results showed high iron content, which indicated that the sample had become contaminated during the cyclone treatment.

(1) Flotation appears to be the most effective operation to remove mica, feldspars, and iron-bearing minerals.

(2) Acid leaching was not entirely successful, although a small quality improvement was possible in every case.

(3) The best results were obtained in test 3 in which Na_2SiO_3 and NaOH were used in the conditioning stage (scrubbing). About 68 percent of the feed was recovered as a sand fraction, containing 0.082 percent Fe_2O_3. After flotation, the cell product assayed 0.043 percent Fe_2O_3 and only 2.7 percent by weight of the flotation feed was removed as a froth waste product. Leaching with 100 g/l HCl at 70°C further lowered the Fe_2O_3 to 0.036 percent. Overall weight recovery was 66 percent.

(4) Removal of oil films from the sand was not seriously considered in tests 1, 2, or 5. In tests 3 and 4, NaOH and Na_2SiO_2 were added to the conditioning stage. No quantitative extraction tests were performed after desliming to evaluate the effectiveness of these reagents for the removal of residual oil.

The various unit processes of scrubbing, desliming, flotation,and leaching could be varied in many ways and could perhaps be combined. Scrubbing may be the most important stage and could be used to break up aggregates of grains and mica books, to remove oil films from the grains, and to disperse solid hydrocarbons.

A suggested method of treatment based on results of this test work is shown in the following flowchart. The activities indicated in the flowchart, that is, scrubbing, classification and flotation, are all standard unit operations in glass sand plants.

Simplified Flowchart of a Suggested Treatment Method

Plant 3 Tailings (-28 mesh)

High density scrubber ← Additives

Slime
Fines
Oil
Mica
(Waste)

H_2O

-100 mesh quartz storage

Cyclones

Flotation cell

Conditioner additives

Froth waste

Glass sand

48
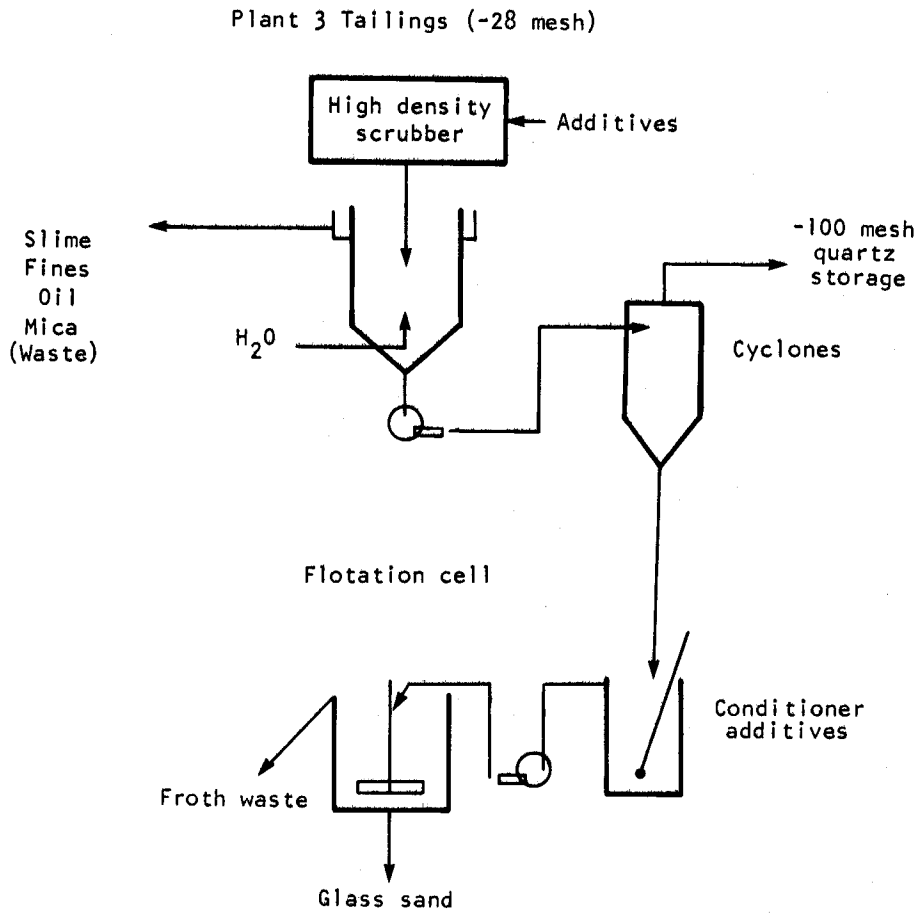
The critical processing step in the flowchart is the *high-density scrubbing*. Additives that should be tested in this step are NaOH, Na_2SiO_3 (various $Na_2O:SiO_2$ ratios), calgon, low-foaming surfactants, or organics that could lower interfacial tension. Acid media scrubbing would not seem to be desirable for several reasons. Phase separation without shear forces should precede the actual desliming-classification in cyclones. Hydroseparators with an up-flow water current may be ideal to wash out the mica and the oil-enriched fines.

Cyclone separation should be in two stages: the first to make a sand product free of -100 mesh particles, and the second to retreat the fines to recover the +100 mesh sand.

Flotation appears to be the most powerful tool to clean up the sand. In the present work only acid circuits were applied, but it might be possible that an alkaline pH, anionic float would produce equal or better results. Some systematic testing with various circuits would quickly point to the most promising reagent scheme.

Leaching should be avoided if possible. Elevated temperatures, washing, and waste disposal problems are extra operating expenses and make handling difficult.

Row 1

Sample 1 (GCOS)

Sample 2 (Cities Service)
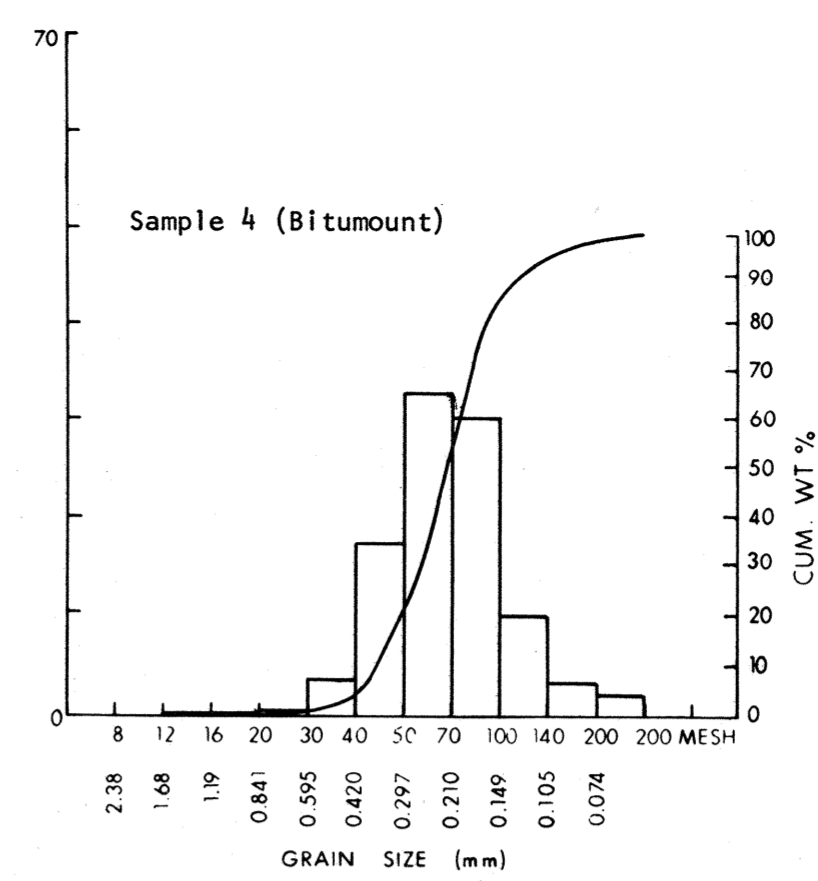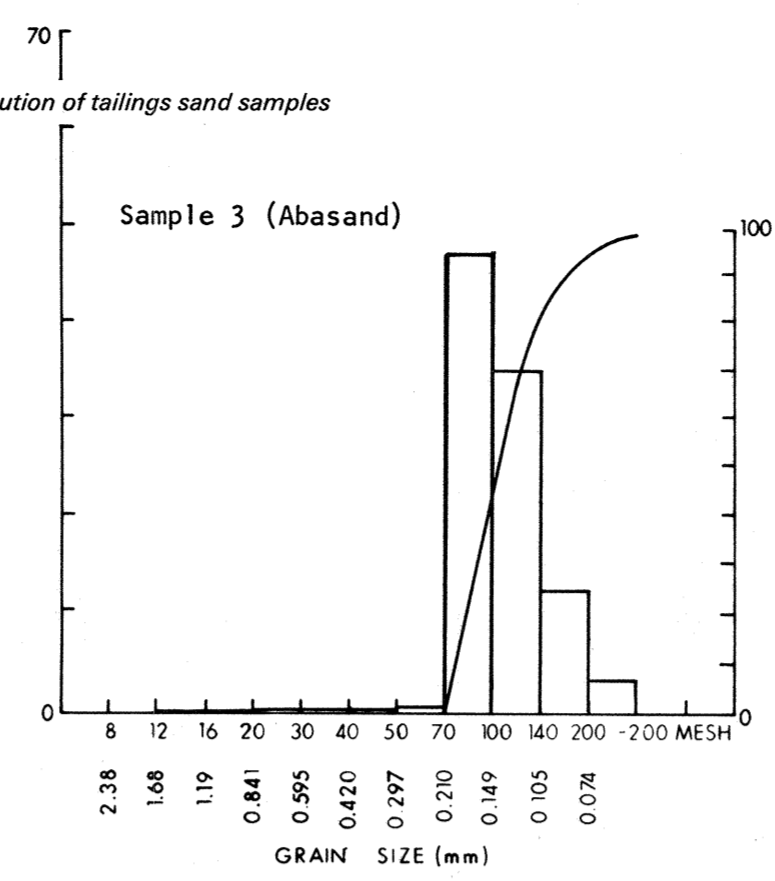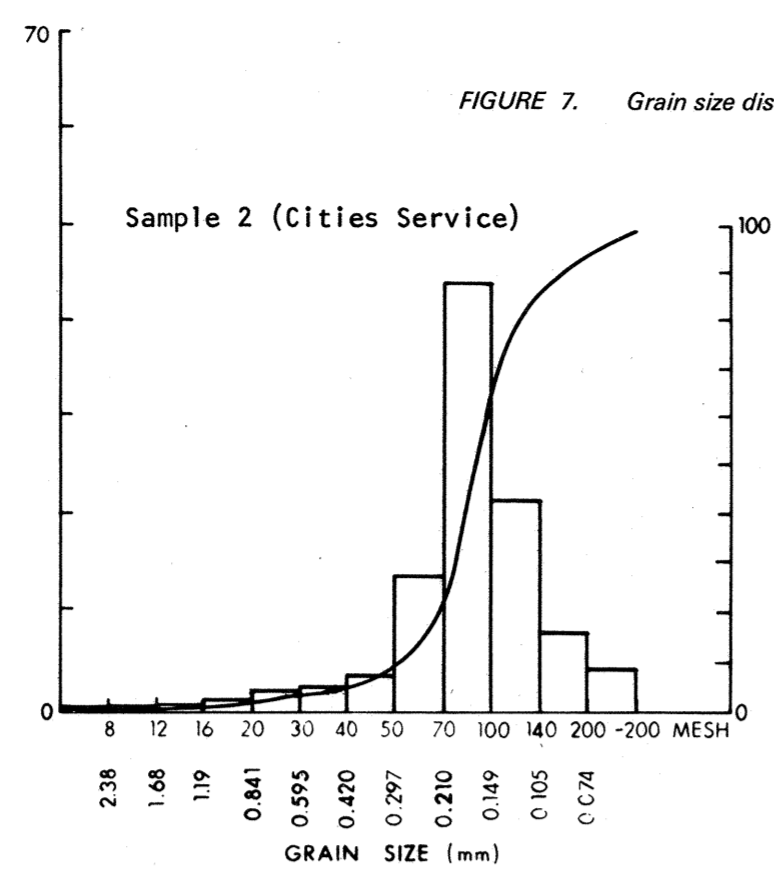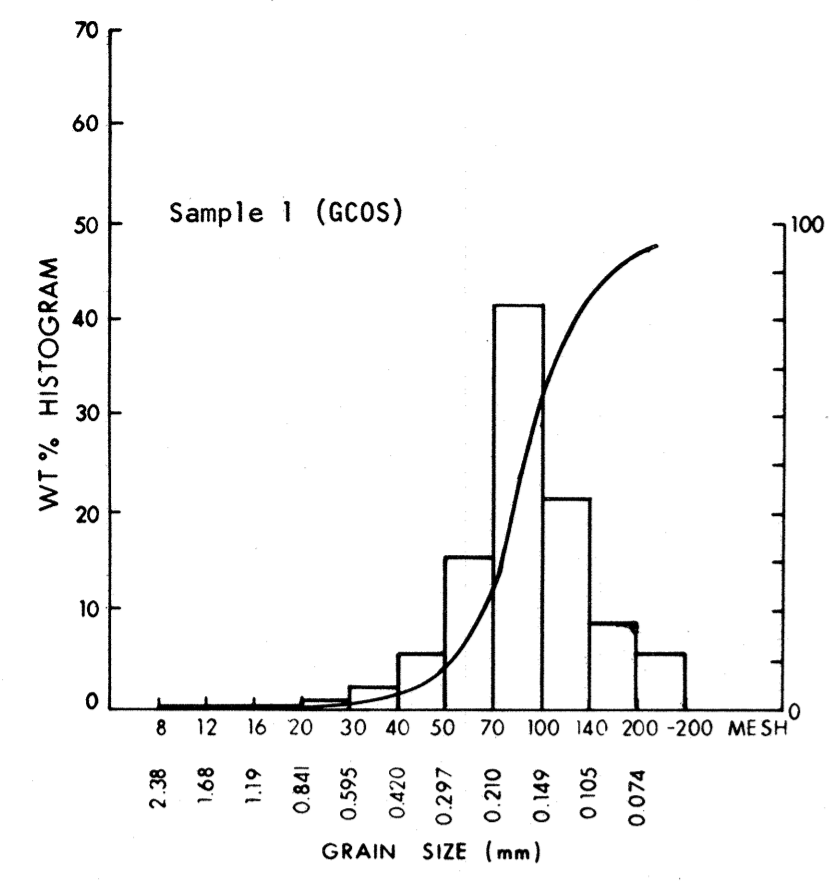
FIGURE 7.   Grain size distribution of tailings sand samples

Sample 3 (Abasand)

Sample 4 (Bitumount)

WT % HISTOGRAM   CUM. WT %
GRAIN SIZE (mm)   MESH

2.38 1.68 1.19 0.841 0.595 0.420 0.297 0.210 0.149 0.105 0.074

8 12 16 20 30 40 50 70 100 140 200 -200

Row 2
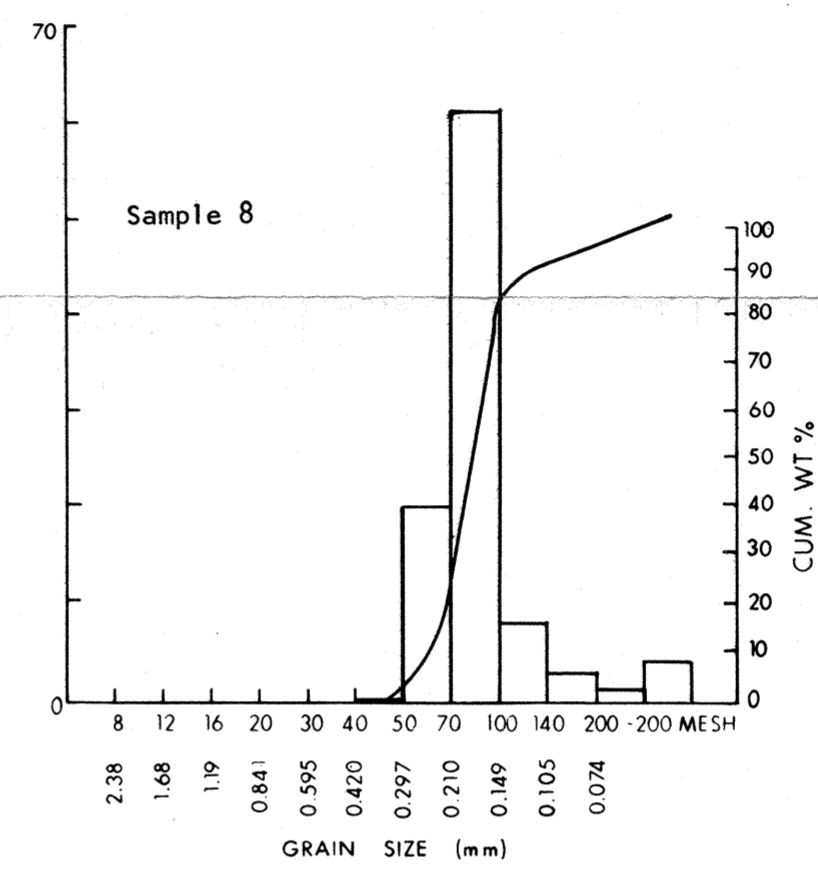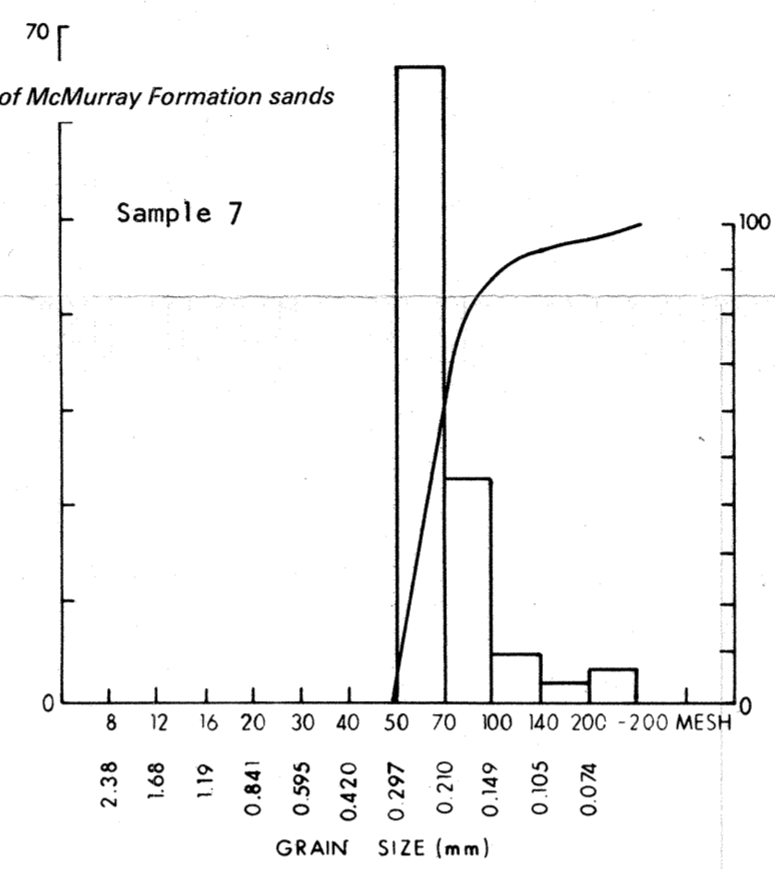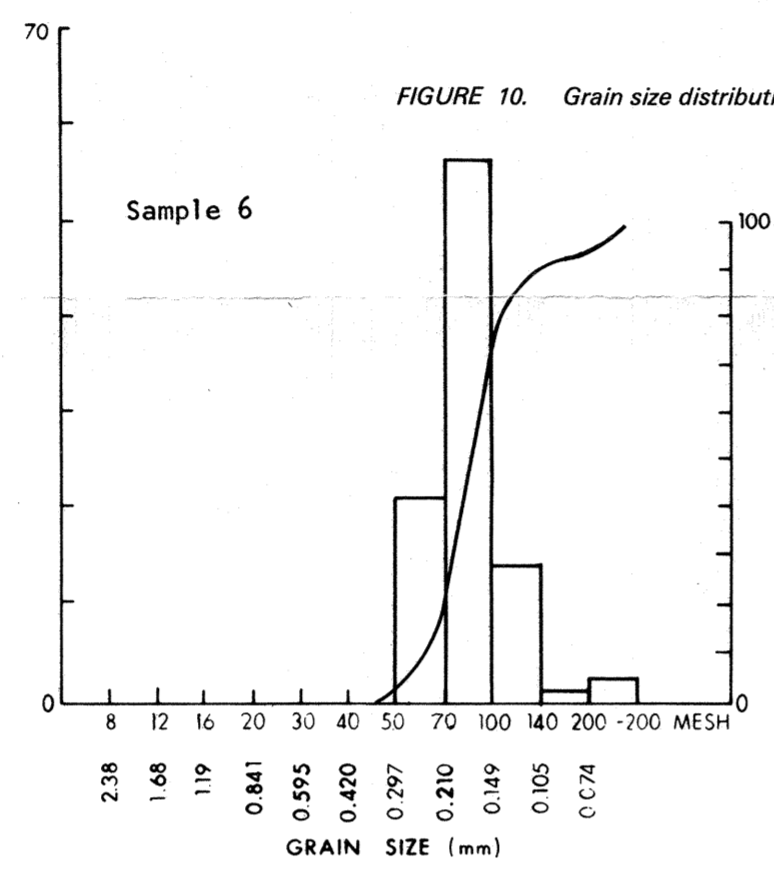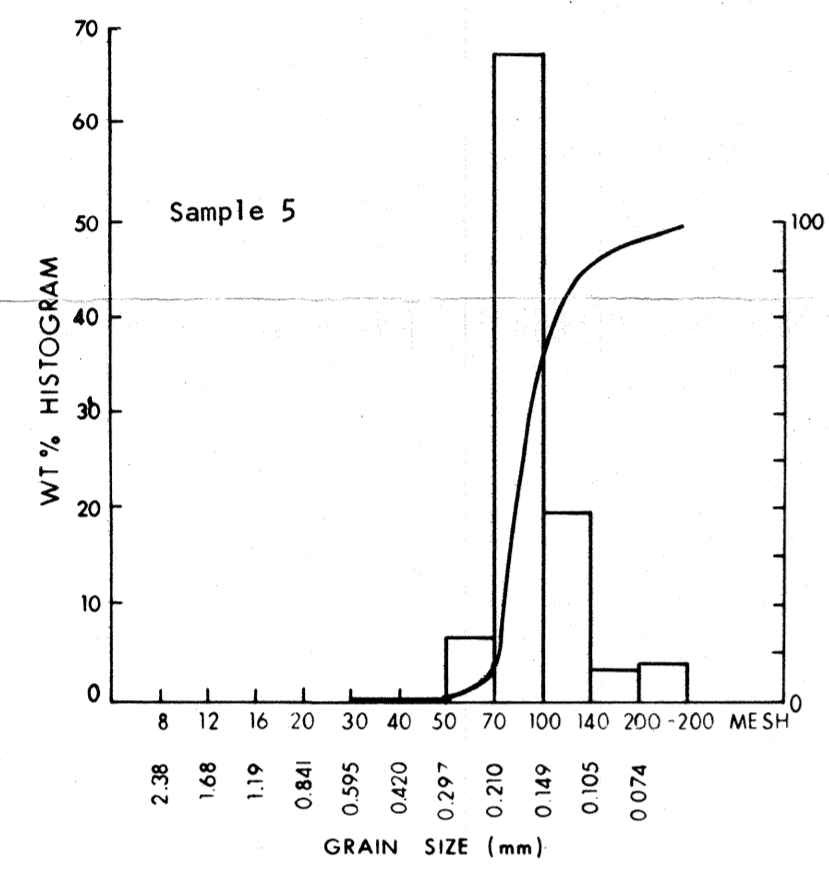
Sample 5

FIGURE 10.   Grain size distribution of McMurray Formation sands

Sample 6

Sample 7

Sample 8

Row 3
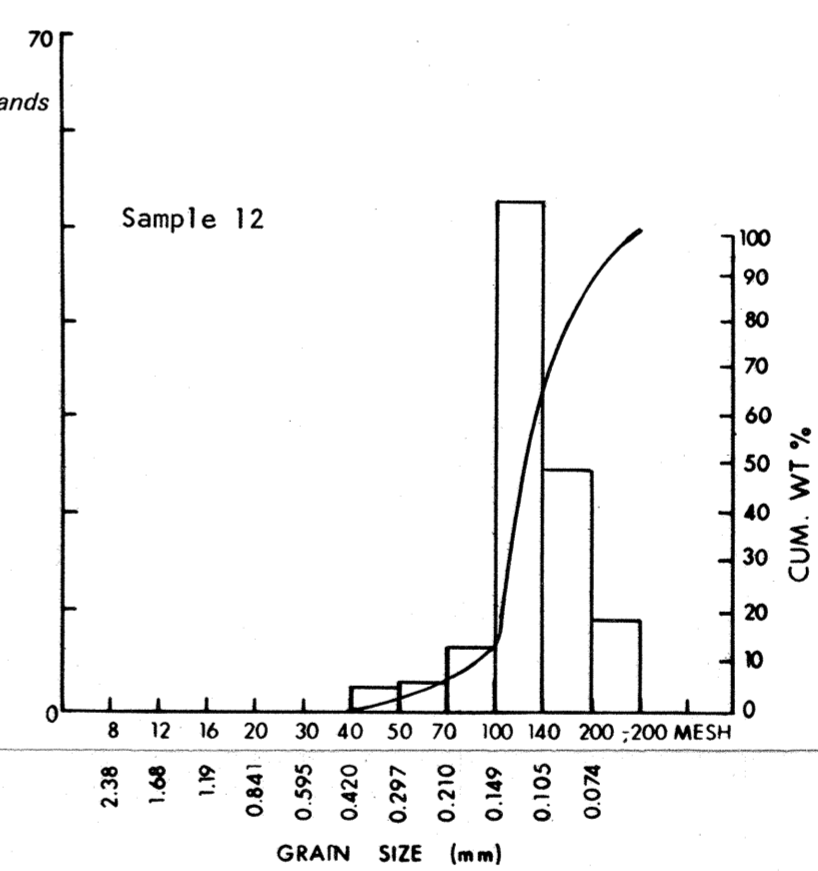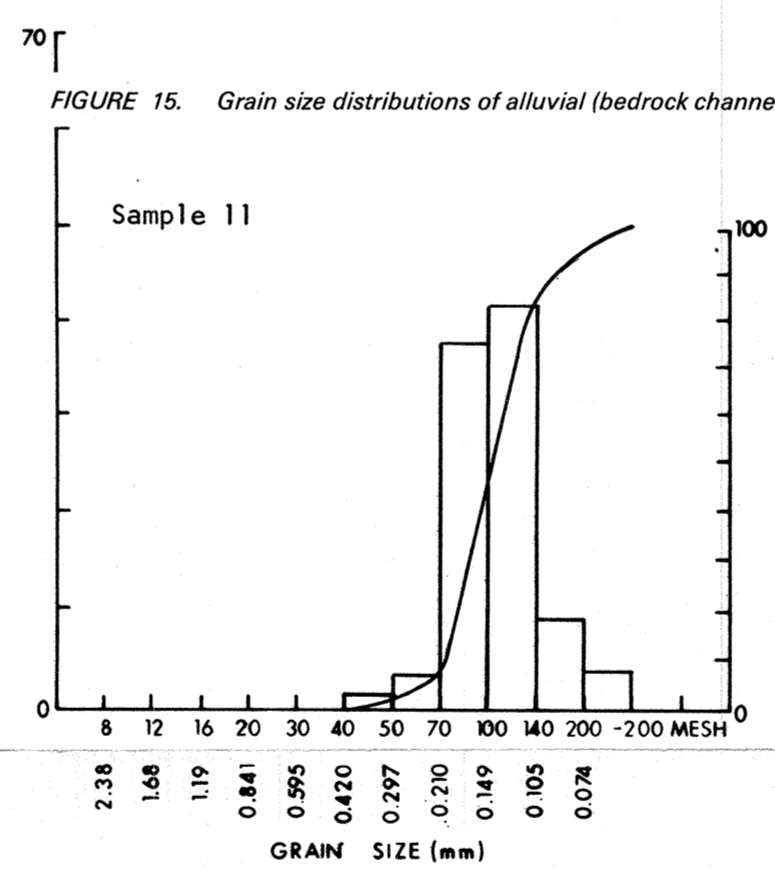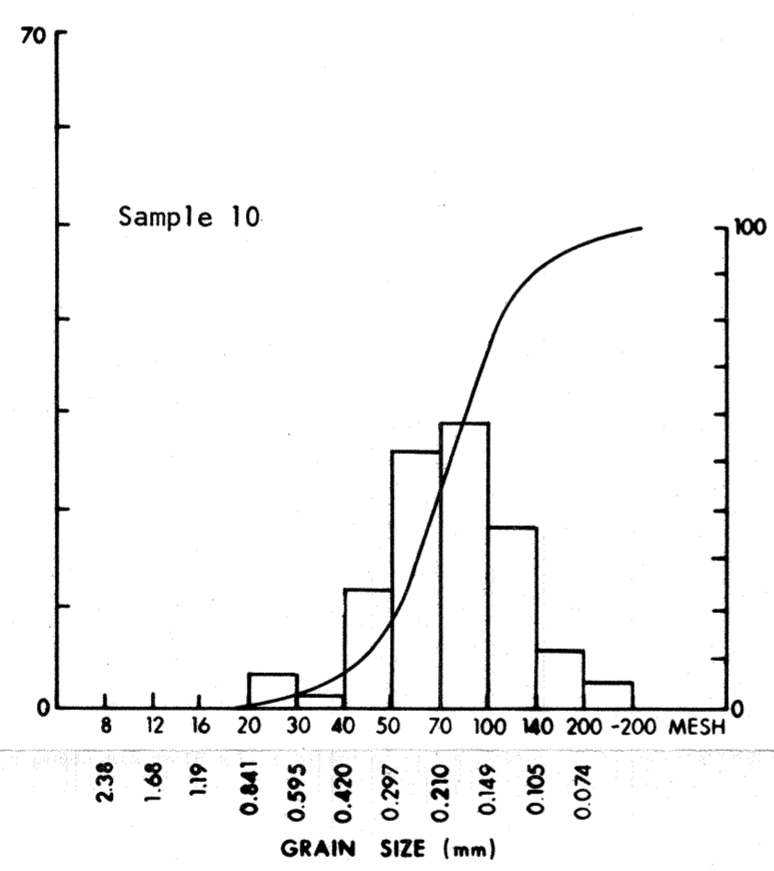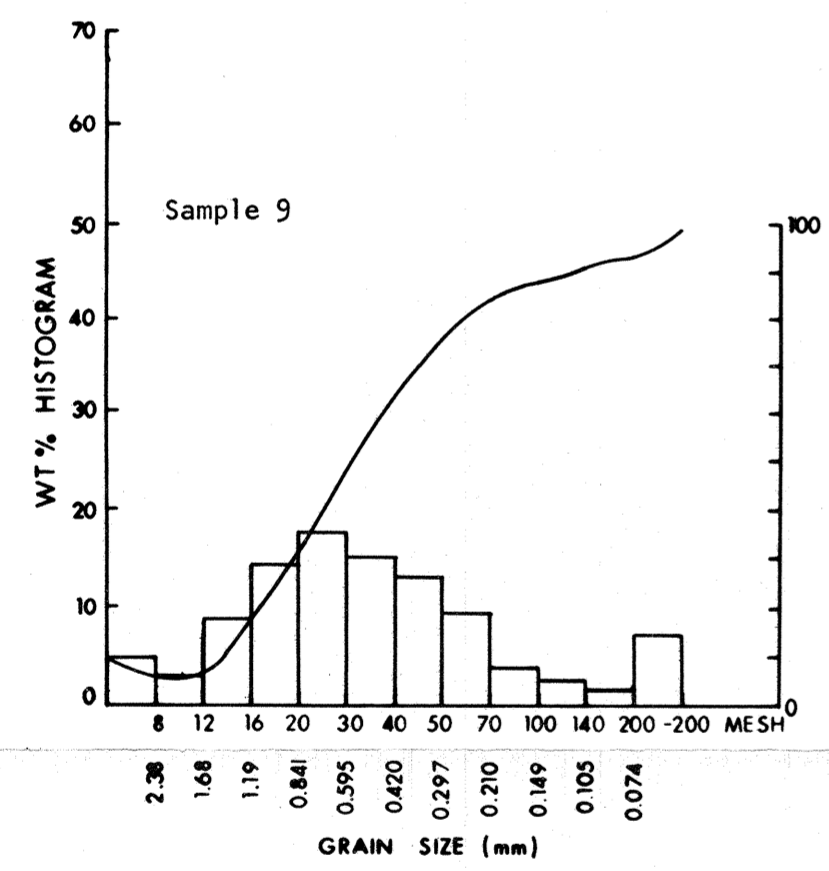
Sample 9

FIGURE 15.   Grain size distributions of alluvial (bedrock channel) sands

Sample 10

Sample 11

Sample 12

Row 4

Sample 13

Sample 14

Sample 15

Sample 16

To accompany
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by I.J. McLaws
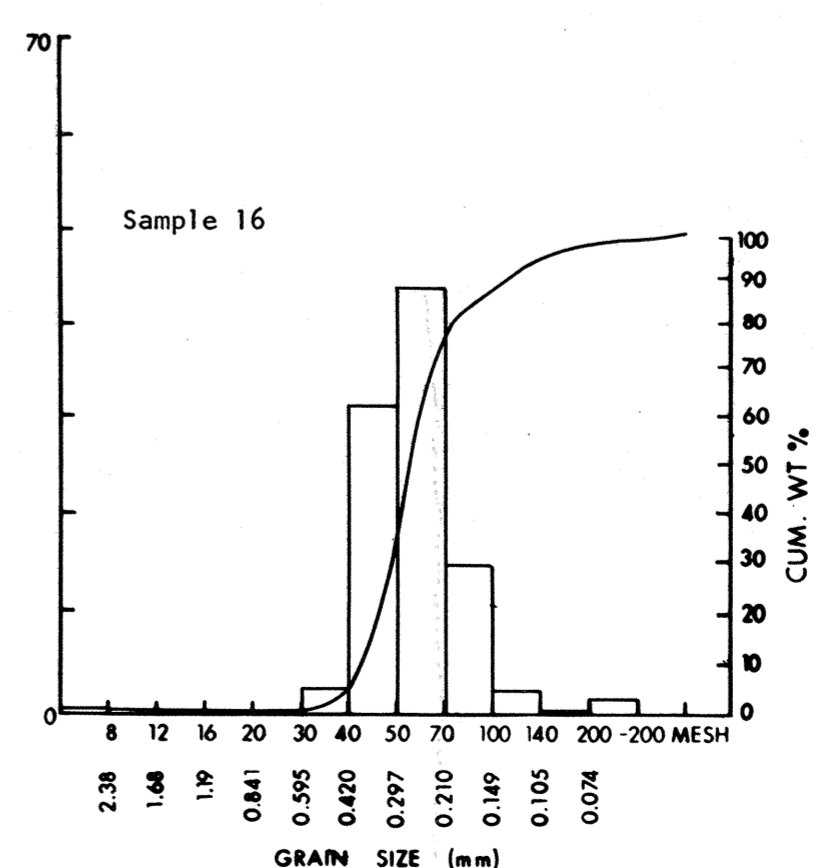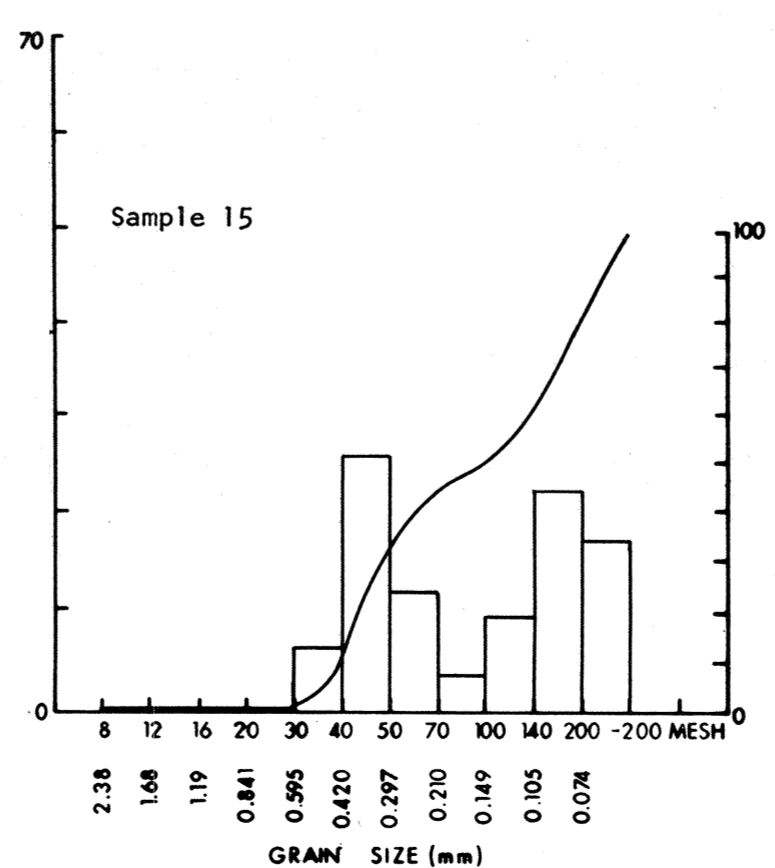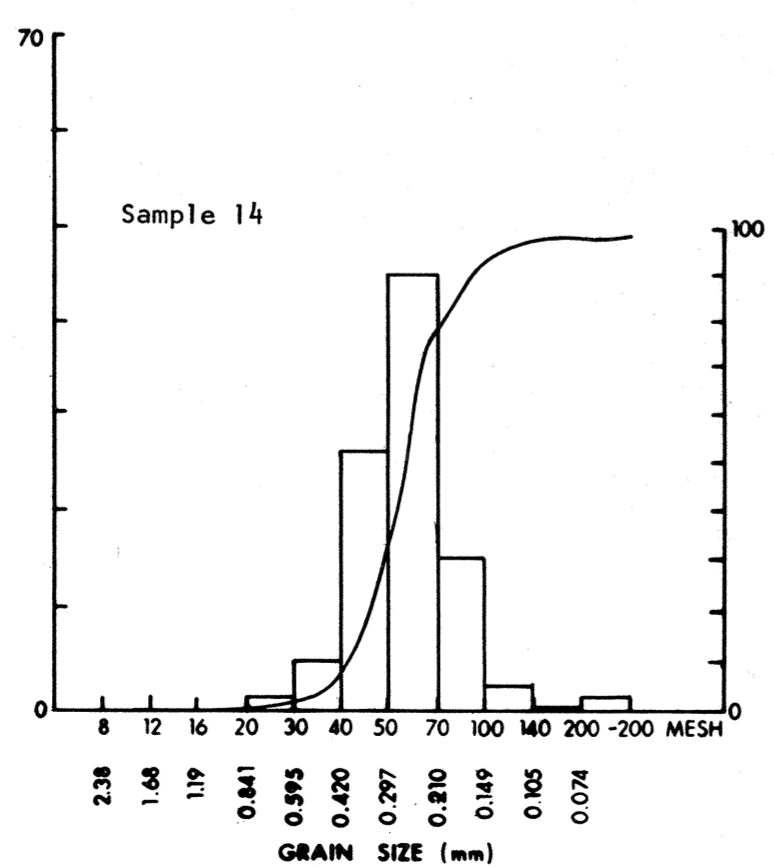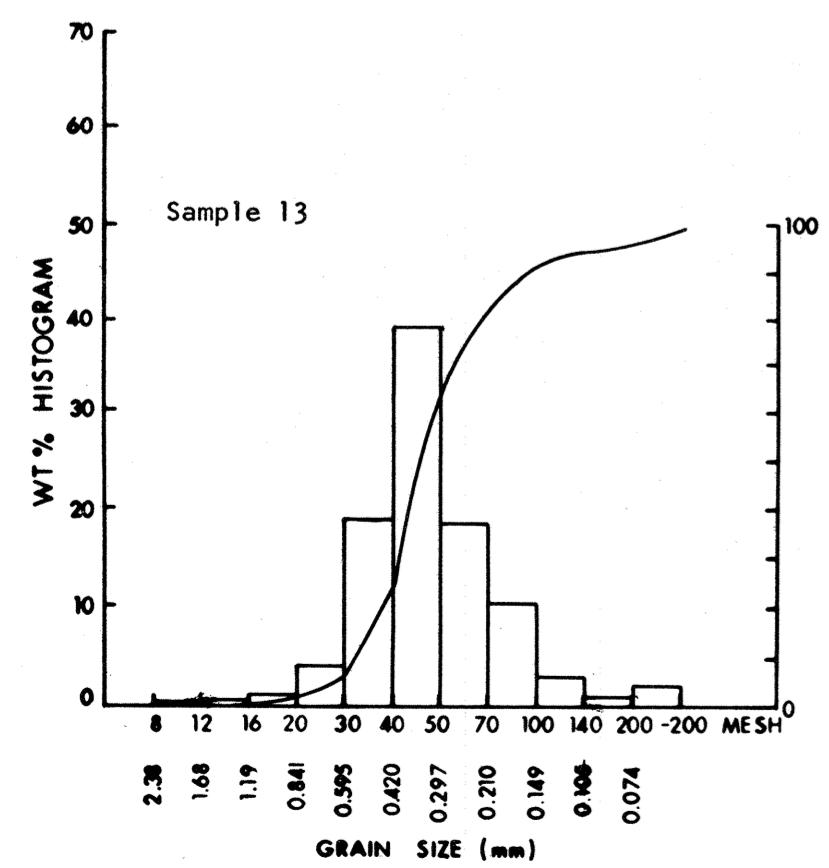
FIGURE 8. *Comparison of grain size distributions of tailings sand samples, showing specified size ranges for (a) glass, and (b) fiberglass manufacturing sands*
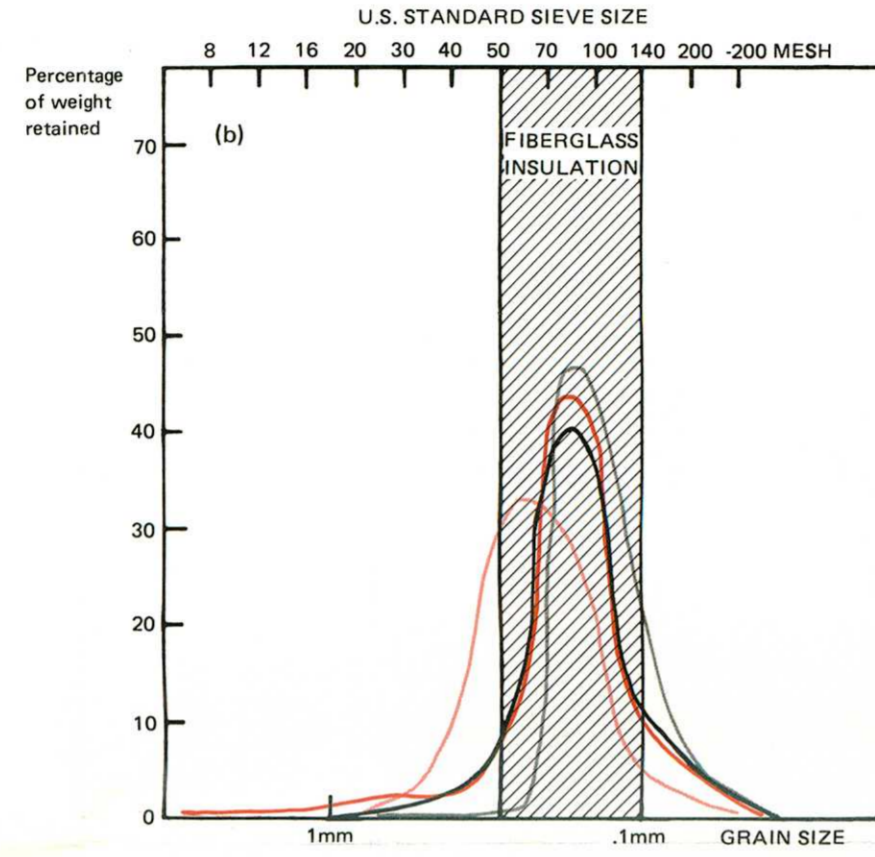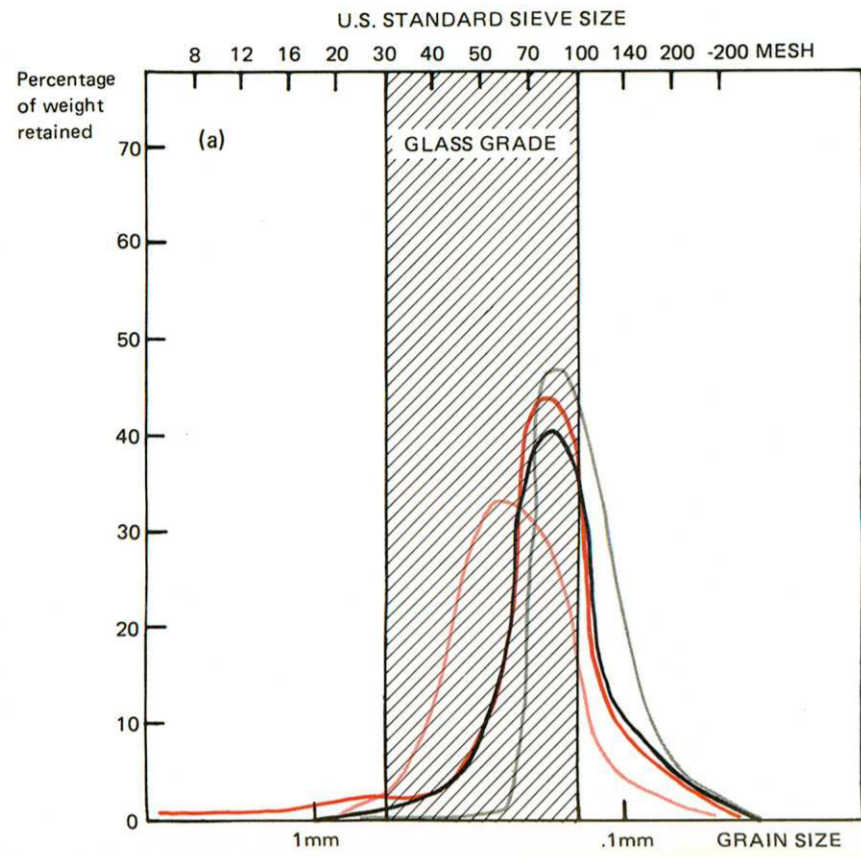
FIGURE 11. *Comparison of grain size distributions of McMurray Formation sands, showing specified size range for (a) glass, and (b) fiberglass manufacturing sands*
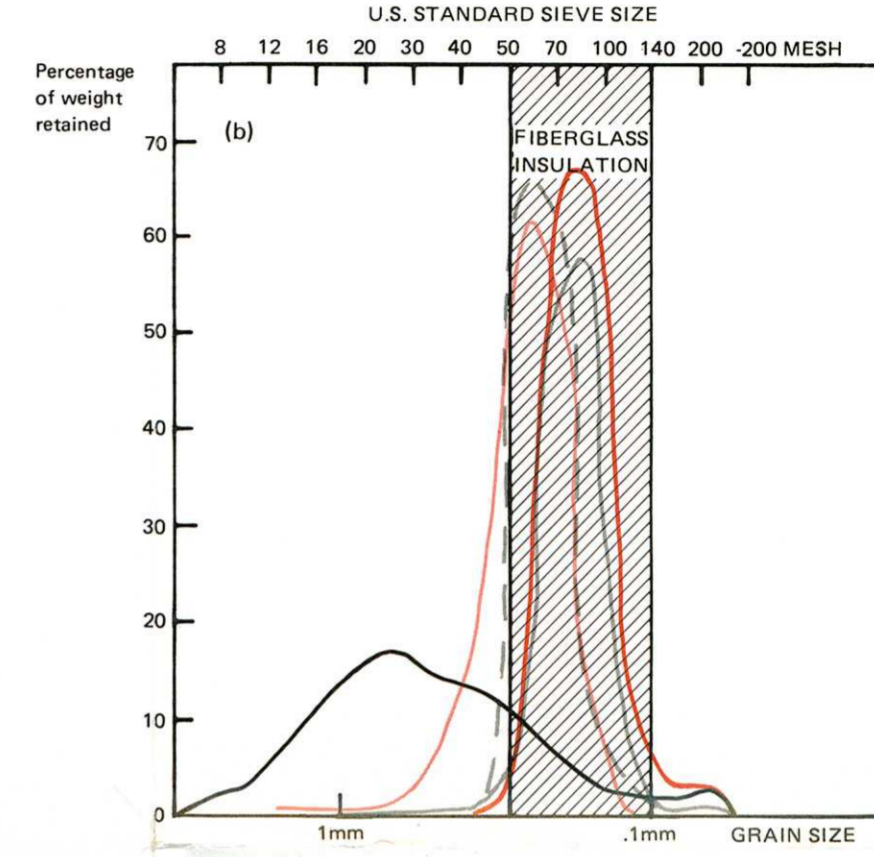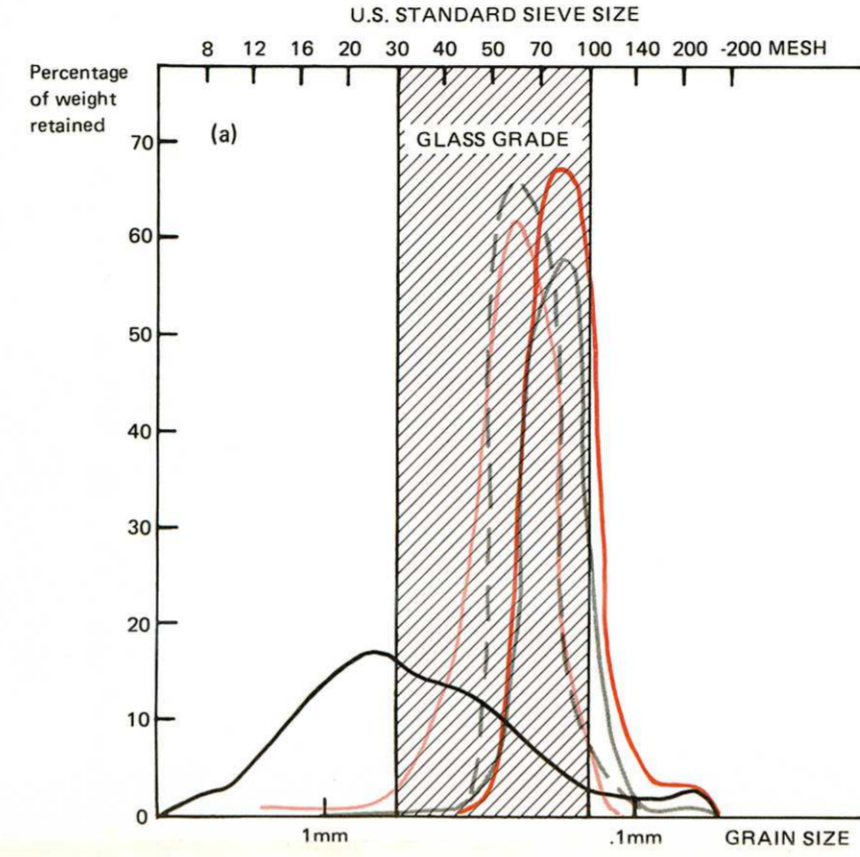
FIGURE 16. *Comparison of grain size distributions of alluvial (bedrock channel) sands, showing specified size range for (a) glass, and (b) fiberglass manufacturing sand*

To accompany
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FIGURE 12. Cross sections of Clearwater River valley illustrating buried bedrock channel
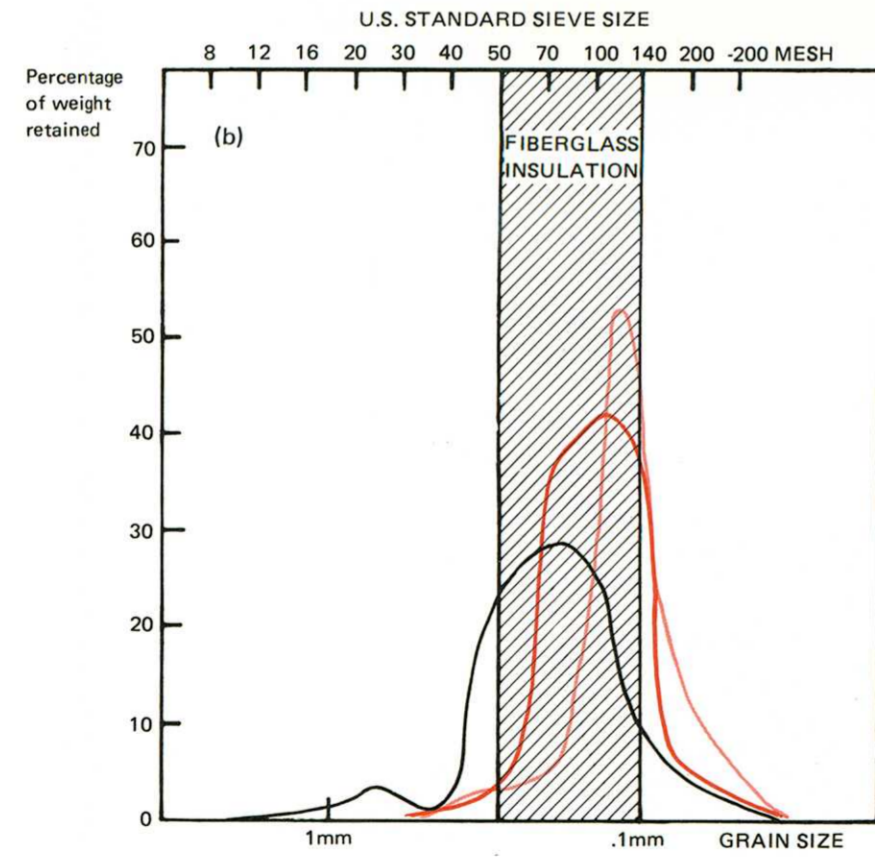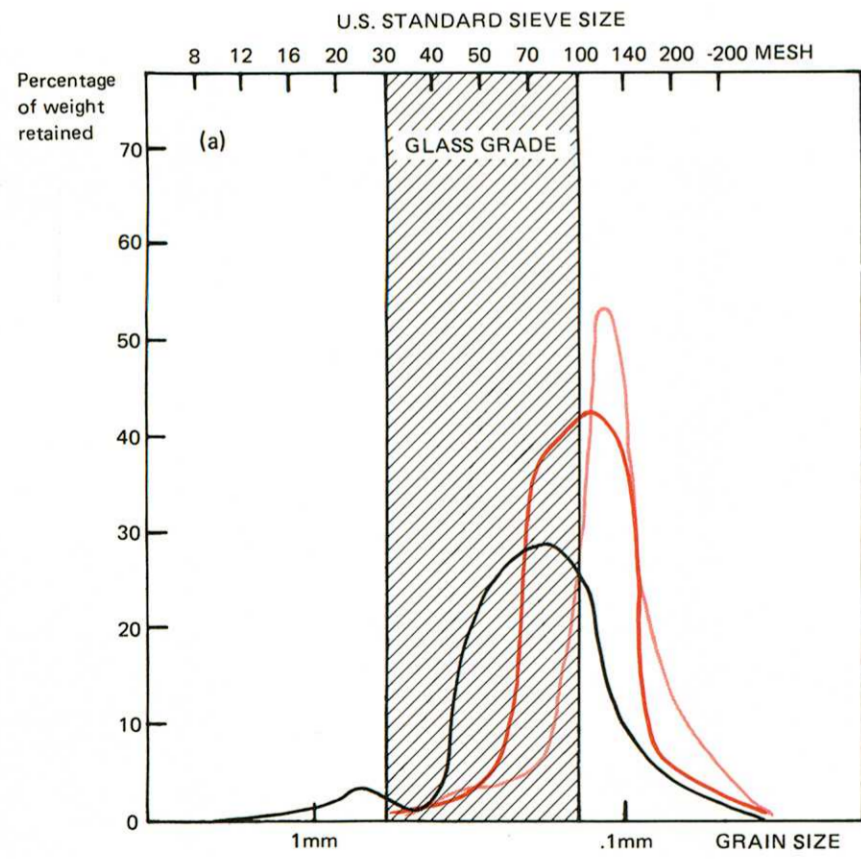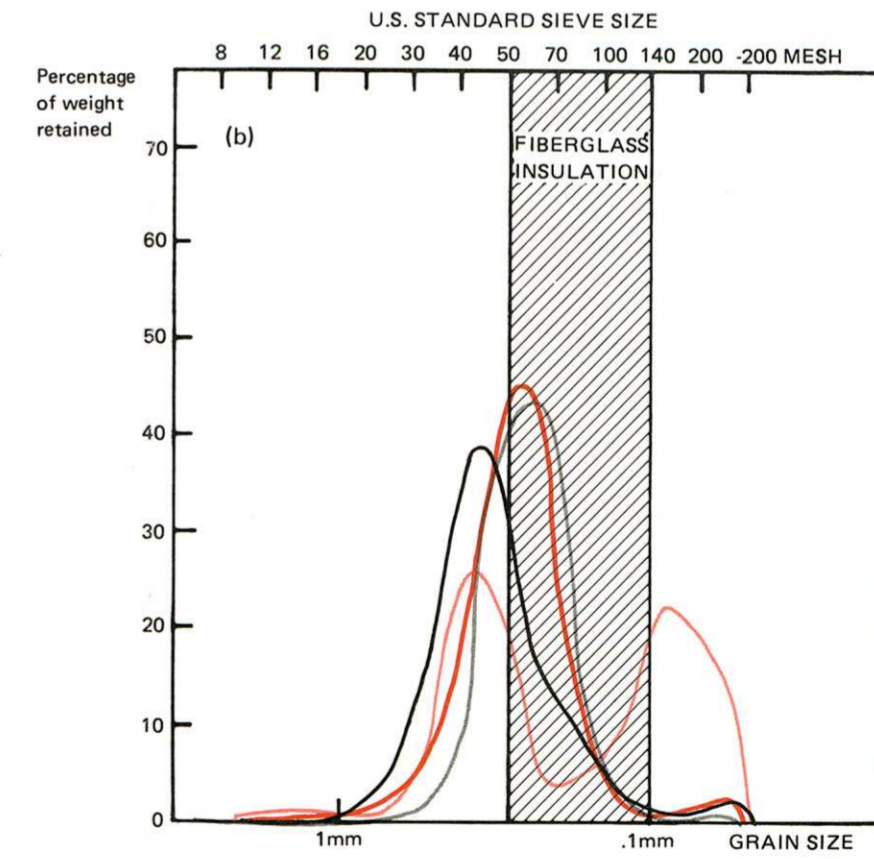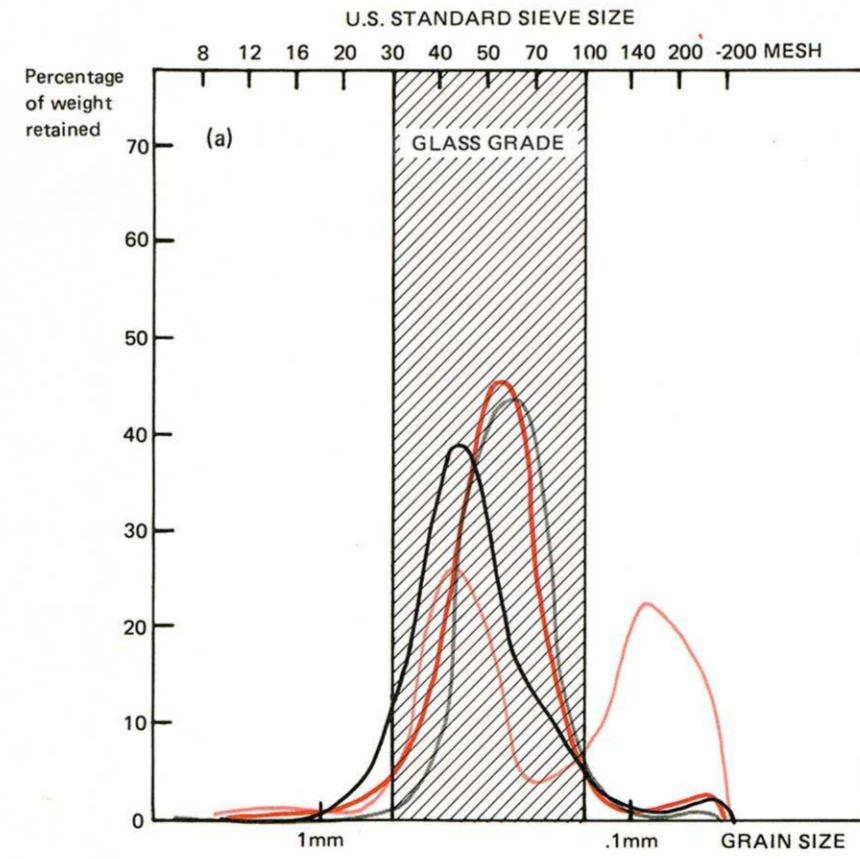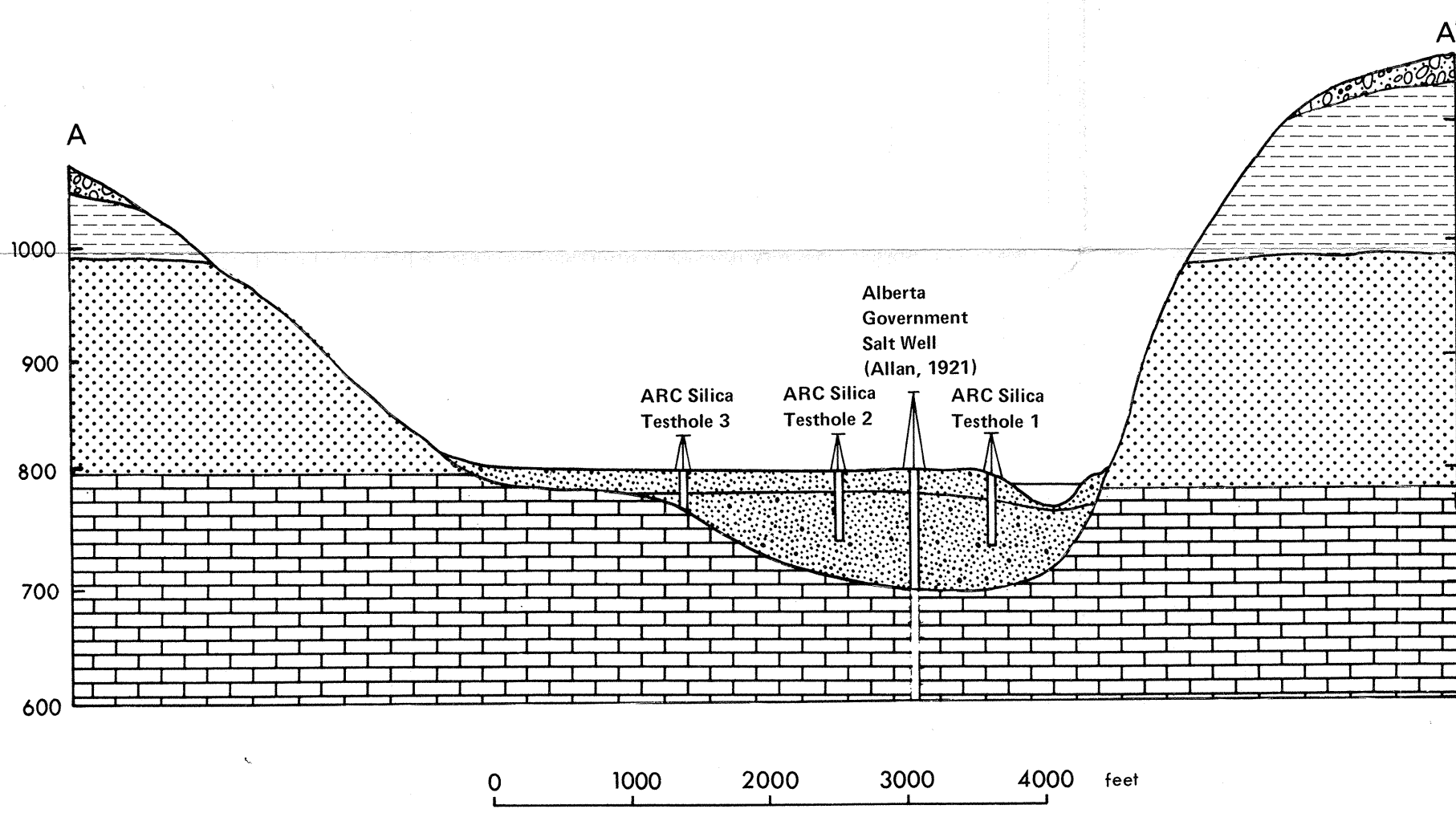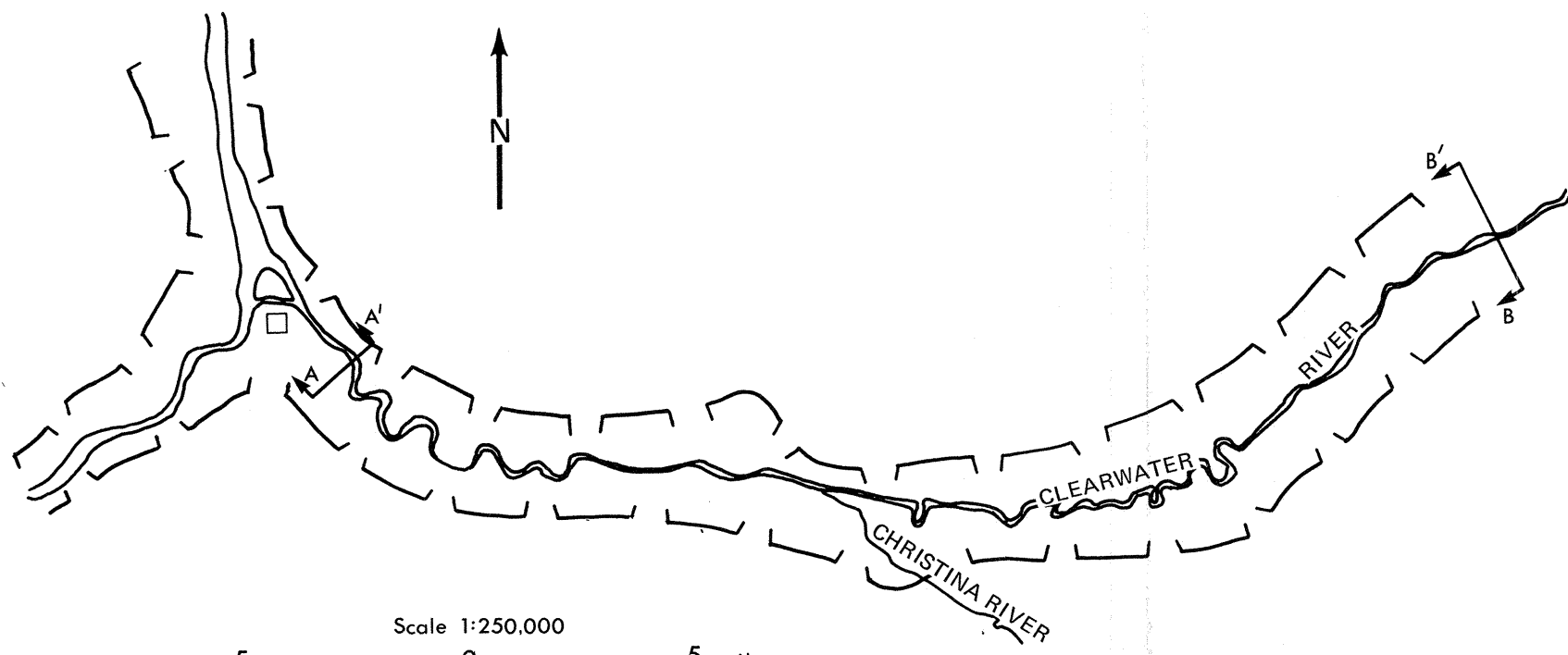
LEGEND

RECENT AND PLEISTOCENE

Tills, sands, and gravels ....

River alluvium ....

LOWER CRETACEOUS

Grand Rapids Formation ....

Clearwater Formation ....

McMurray Formation ....

UPPER DEVONIAN

Waterways Formation ....

MIDDLE DEVONIAN

Upper Elk Point Group ....

Location of Alberta Research Council testhole ....

Line of cross-section ....

Upper topographic boundary of Clearwater River
valley ....

Scale 1:250,000

5   0   5 miles

Alberta
Government
Salt Well
(Allan, 1921)

ARC Silica   ARC Silica   ARC Silica
Testhole 3   Testhole 2   Testhole 1

0   1000   2000   3000   4000   feet

RCA Gypsum Testhole B
(Hamilton, 1969)

0   1000   2000   3000   4000   feet

FIGURE 17. Grain size distribution of eolian sands

Table 1. Textural Analyses of Silica Sands from the Fort McMurray Area

Sample Number	Type of Sample	8 (2.38)[1]	12 (1.68)	16 (1.19)	20 (0.841) Roundness[2]	30 (0.595) Roundness	40 (0.420) Roundness	50 (0.297) Roundness	70 (0.210) Roundness	100 (0.149) Roundness	140 (0.105)	200 (0.074)	Silt (%)	Clay (<5μ) (%)
1	oil sand tailings (GCOS)	0.00	0.01	0.05	0.16	0.80	2.07	5.11	15.24	41.51	21.25	8.48	4.22	1.10
		-	-	-	-	.25r	.19r	.20r	.22r	.22r	-	-	-	-
2	oil sand tailings (Cities Service)	0.22	0.11	0.41	0.99	1.81	2.15	3.54	13.36	44.17	21.30	7.78	3.64	0.52
		-	-	-	-	.31r	.37r	.32r	.30r	.31r	-	-	-	-
3	oil sand tailings (Abasand)	0.00	0.00	0.01	0.01	0.03	0.05	0.09	0.68	47.58	35.49	12.40	2.67	0.99
		-	-	-	-	-	.34r	.34r	.25r	.29r	-	-	-	-
4	oil sand tailings (Bitumount)	0.00	0.00	0.03	0.07	0.34	3.41	17.39	33.31	30.39	9.85	3.20	1.80	0.21
		-	-	-	-	.40r	.34r	.27r	.27r	.23r	-	-	-	-
5	McMurray Formation bedrock sand: 0-10 ft (0-3 m)	0.00	0.00	0.00	0.00	0.00	0.01	0.02	6.46	67.54	19.45	3.00	2.15	1.37
		-	-	-	-	-	-	-	.27r	.32r	-	-	-	-
6	McMurray Formation bedrock sand: 10-30 ft (3-9 m)	0.00	0.00	0.00	0.00	0.00	0.00	0.03	20.20	56.96	13.79	2.84	3.45	2.73
		-	-	-	-	-	-	.30r	.29r	.31r	-	-	-	-
7	McMurray Formation bedrock sand: 30-45 ft (9-14 m)	0.00	0.00	0.00	0.00	0.00	0.00	0.22	66.60	23.18	4.95	1.79	1.97	1.29
		-	-	-	-	-	-	.29r	.32r	.34r	-	-	-	-
8	McMurray Formation bedrock sand: 45-60 ft (14-18 m)	0.00	0.00	0.01	0.07	0.44	1.97	21.09	62.87	7.87	2.28	1.09	1.56	0.75
		-	-	-	-	.31r	.34r	.34r	.34r	.30r	-	-	-	-
9	McMurray Formation bedrock sand: 60-63 ft (18-19 m)	4.56	2.83	8.88	14.18	17.48	15.03	12.93	9.28	3.69	2.51	1.51	4.82	2.30
		-	-	-	.33r	.29r	.30r	.31r	.29r	.27r	-	-	-	-

Testhole 1

Sample Number	Type of Sample	8	12	16	20	30	40	50	70	100	140	200	Silt (%)	Clay (%)
10	alluvial (bedrock channel) sand: 20-40 ft (6-12 m)	0.03	0.04	0.04	0.08	3.42	1.21	12.19	26.52	29.38	18.50	5.98	2.50	0.11
		-	-	-	-	.34r	.36r	.31r	.32r	.30r	-	-	-	-
11	alluvial (bedrock channel) sand: 40-50 ft (12-15 m)	0.00	0.03	0.03	0.05	0.14	0.29	1.68	3.82	38.20	42.16	9.60	3.23	0.77
		-	-	-	-	.34r	.33r	.32r	.28r	.26r	-	-	-	-
12	alluvial (bedrock channel) sand: 50-60 ft (15-18 m)	0.00	0.00	0.02	0.06	0.08	0.19	2.55	2.99	6.54	53.10	24.85	8.83	0.79
		-	-	-	-	-	.36r	.32r	.38r	.28r	-	-	-	-

Testhole 2

Sample Number	Type of Sample	8	12	16	20	30	40	50	70	100	140	200	Silt (%)	Clay (%)
13	alluvial (bedrock channel) sand: 20-25 ft (6-8 m)	0.00	0.13	0.43	1.03	4.37	18.80	39.50	18.71	10.46	3.14	0.84	1.52	1.07
		-	-	-	-	.34r	.34r	.32r	.34r	.30r	-	-	-	-
14	alluvial (bedrock channel) sand: 25-45 ft (8-14 m)	0.04	0.06	0.14	0.33	1.45	5.23	26.73	45.56	15.61	2.67	0.50	0.96	0.72
		-	-	-	-	.34r	.36r	.31r	.27r	.29r	-	-	-	-
15	alluvial (bedrock channel) sand: 45-65 ft (14-20 m)	0.00	0.17	0.03	0.09	0.66	6.89	26.28	11.95	3.91	9.77	22.74	16.80	0.71
		-	-	-	-	-	.31r	.28r	.31r	.29r	-	-	-	-

Testhole 3

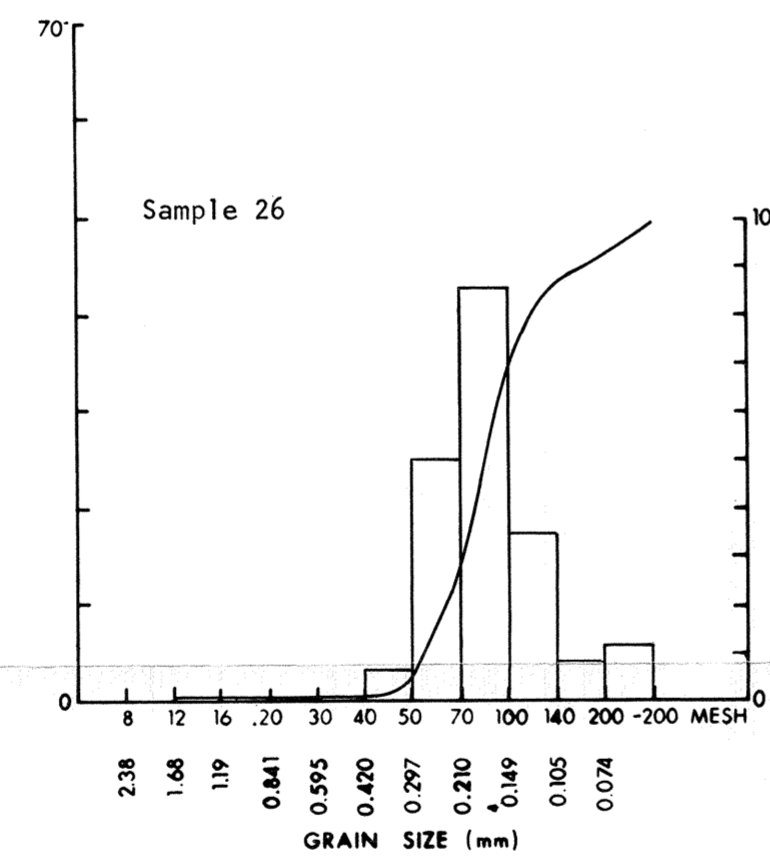| Sample Number	Type of Sample	8	12	16	20	30	40	50	70	100	140	200	Silt (%)	Clay (%)
16	alluvial (bedrock channel) sand: 20-30 ft (6-9 m)	0.65	0.09	0.12	0.16	0.38	2.68	31.40	44.39	15.06	2.55	0.66	1.16	0.70
		-	-	-	- •	.28r	.38r	.29r	.33r	.26r	-	-	-	-
17	dune sand: 3-13 ft (1-4 m)	0.00	0.00	0.00	0.01	0.37	4.32	30.63	46.86	14.63	2.48	0.47	0.13	0.10
		-	-	-	-	.33r	.32r	.30r	.29r	.33r	-	-	-	-
18	dune sand: 13-23 ft (4-7 m)	0.06	0.05	0.06	0.05	0.26	1.66	21.70	54.35	18.17	2.66	0.39	0.45	0.14
		-	-	-	-	-	.32r	.29r	.28r	.28r	-	-	-	-
19	dune sand	0.00	0.00	0.02	0.05	0.36	0.89	1.67	5.09	15.12	34.30	28.62	6.83	7.05
		-	-	-	-	.31r	.33r	.34r	.23r	.26r	-	-	-	-
20	dune sand	0.00	0.00	0.02	0.00	0.00	0.05	0.65	6.56	23.00	32.39	20.26	10.74	6.33
		-	-	-	-	-	.31r	.27r	.23r	.26r	-	-	-	-
21	dune sand	0.00	0.00	0.00	0.00	0.02	0.07	0.92	4.75	16.83	36.67	24.96	9.55	6.23
		-	-	-	-	-	.33r	.28r	.28r	.29r	-	-	-	-
22	dune sand	0.00	0.00	0.00	0.02	0.22	0.16	15.25	41.09	28.86	8.64	1.55	2.98	1.23
		-	-	-	-	-	.29r	.30r	.22r	.27r	-	-	-	-
23	dune sand	0.00	0.00	0.00	0.00	0.01	0.34	11.31	39.79	31.52	12.85	2.54	0.52	1.12
		-	-	-	-	-	.20r	.26r	.26r	.24r	-	-	-	-
24	dune sand	0.00	0.00	0.00	0.04	0.56	2.17	10.20	19.20	24.03	21.16	14.41	5.84	2.39
		-	-	-	-	.37r	.38r	.31r	.31r	.29r	-	-	-	-
25	dune sand	0.13	0.00	0.02	0.20	1.41	5.95	17.53	22.04	18.54	14.11	9.46	9.20	1.41
		-	-	-	-	.36r	.36r	.35r	.32r	.26r	-	-	-	-
26	dune sand	0.00	0.00	0.02	0.06	0.16	0.21	3.22	25.23	42.68	17.54	4.08	3.31	3.49
		-	-	-	-	.19r	.23r	.26r	.30r	.29r	-	-	-	-
27	dune sand	0.00	0.00	0.00	0.00	0.03	0.16	1.68	13.54	48.68	23.92	6.56	3.80	1.63
		-	-	-	-	-	.30r	.27r	.26r	.30r	-	-	-	-
28	dune sand	0.00	0.00	0.00	0.03	0.51	2.18	10.17	18.94	23.38	19.20	12.95	10.45	2.19
		-	-	-	-	.39r	.38r	.35r	.31r	.29r	-	-	-	-
29	dune sand	0.00	0.00	0.00	0.02	0.32	2.52	11.47	24.27	30.00	20.54	7.98	1.76	1.12
		-	-	-	-	-	.39r	.36r	.31r	.32r	-	-	-	-

[1] Screen size (mm) corresponding to sieve number.

[2] Script numbers followed by the letter r refer to *average grain roundness* of the sand grains in that fraction. Roundness is expressed numerically as some value between 0 and 1, a perfectly rounded grain having a roundness of 1 (see Appendix B). The *average* roundness values are calculated from grain count data based on visual comparison of grain shapes with standard roundness images.

Table 2.   Mineral Composition and Iron Staining of Sands from the Fort McMurray Area

Sample Number	Type of Sample		Mineral Composition (100 grain count)					Heavy Minerals[†] (Wt. %)	Magnetic Minerals[†] (Wt. %)			Iron Staining (100 grain count)				
			Quartz	Feldspar	Chert	Mica	Others[1]		0.1 amp[2]	0.9 amp	1.7 amp	Heavy	Medium	Light	Inclusions	Clear
1	oil sand tailings (GCOS)	A*	94	4	1	0	1	-	-	-	-	1	15	35	1	48
		B -70+100	94	4	1	0	1	0.05	-	-	-	1	13	35	0	51
		C -30+100	-	-	-	-	-	0.09	0.02	0.25	0.36	-	-	-	-	-
2	oil sand tailings (Cities Service)	A	95	2	1	1	1	-	-	-	-	1	10	55	0	34
		B -70+100	95	2	1	1	1	0.05	-	-	-	0	12	58	0	30
		C -30+100	-	-	-	-	-	0.07	<0.01	0.15	0.23	-	-	-	-	-
3	oil sand tailings (Abasand)	A	96	1	0	1	2	-	-	-	-	0	25	42	0	33
		B -70+100	96	1	0	1	2	-	-	-	-	0	25	42	0	33
		C -30+100	-	-	-	-	-	0.04	<0.01	0.08	0.13	-	-	-	-	-
4	oil sand tailings (Bitumount)	A	95	2	1	0	2	-	-	-	-	5	13	57	2	23
		B -50+70	94	3	1	1	1	0.13	-	-	-	0	12	74	0	14
		C -30+100	-	-	-	-	-	-	0.01	0.86	1.36	-	-	-	-	-
5	McMurray Formation bedrock sand: 0-10 ft (0-3 m)	A	94	4	1	1	0	-	-	-	-	0	6	80	0	14
		B -70+100	95	4	1	0	0	0.14	0.04	0.92	1.04	0	5	81	0	14
6	McMurray Formation bedrock sand: 10-30 ft (3-9 m)	A	93	3	2	1	1	-	-	-	-	0	10	53	0	37
		B -70+100	94	2	2	1	1	0.08	0.01	0.15	0.18	0	11	49	0	40
7	McMurray Formation bedrock sand: 30-45 ft (9-14 m)	A	98	1	0	0	1	-	-	-	-	0	1	65	0	34
		B -50+70	98	1	0	0	1	0.14	0.01	0.15	0.32	0	1	61	0	38
8	McMurray Formation bedrock sand: 45-60 ft (14-18 m)	A	98	1	0	0	1	-	-	-	-	1	2	73	0	24
		B -50+70	97	1	1	0	1	0.13	0.01	0.14	0.18	0	0	65	0	35
9	McMurray Formation bedrock sand: 60-63 ft (18-19 m)	A	98	1	0	0	1	-	-	-	-	0	1	65	0	34
		B -20+30	98	2	0	0	0	0.13	-	-	-	0	1	56	1	42

Testhole 1

Sample Number	Type of Sample		Quartz	Feldspar	Chert	Mica	Others[1]	Heavy Minerals (Wt. %)	0.1 amp	0.9 amp	1.7 amp	Heavy	Medium	Light	Inclusions	Clear
10	alluvial (bedrock channel) sand: 20-40 ft (6-12 m)	A	95	3	0	0	2	-	-	-	-	2	10	51	3	34
		B -70+100	97	3	0	0	0	0.16	0.01	0.46	0.75	1	10	59	0	30
11	alluvial (bedrock channel) sand: 40-50 ft (12-15 m)	A	94	3	1	1	1	-	-	-	-	1	7	53	1	38
		B -100+140	-	-	-	-	-	0.25	0.06	0.95	1.38	-	-	-	-	-
12	alluvial (bedrock channel) sand: 50-60 ft (15-18 m)	A	95	3	1	0	1	-	-	-	-	0	9	59	1	31
		B -100+140	95	3	1	0	1	0.21	0.06	1.00	1.33	0	9	59	1	31

Testhole 2

Sample Number	Type of Sample		Quartz	Feldspar	Chert	Mica	Others[1]	Heavy Minerals (Wt. %)	0.1 amp	0.9 amp	1.7 amp	Heavy	Medium	Light	Inclusions	Clear
13	alluvial (bedrock channel) sand: 20-25 ft (6-8 m)	A	90	6	2	0	2	-	-	-	-	4	8	68	3	17
		B -40+50	90	6	3	0	1	0.30	0.03	0.57	0.91	5	9	63	3	20
14	alluvial (bedrock channel) sand: 25-45 ft (8-14 m)	A	90	7	1	0	2	-	-	-	-	0	4	67	1	28
		B -50+70	94	6	0	0	0	0.17	0.03	0.47	0.79	0	1	67	2	30
15	alluvial (bedrock channel) sand: 45-65 ft (14-20 m)	A	90	7	1	0	2	-	-	-	-	0	15	66	3	16
		B -40+50	91	8	0	0	1	0.18	0.06	1.41	1.53	0	18	62	3	17

Testhole 3

Sample Number	Type of Sample		Quartz	Feldspar	Chert	Mica	Others[1]	Heavy Minerals (Wt. %)	0.1 amp	0.9 amp	1.7 amp	Heavy	Medium	Light	Inclusions	Clear
16	alluvial (bedrock channel) sand: 20-30 ft (6-9 m)	A	92	7	1	0	0	-	-	-	-	1	2	80	0	17
		B -50+70	93	6	1	0	0	0.15	0.02	0.29	0.51	2	0	81	0	17
17	dune sand: 3-13 ft (1-4 m)	A	98	2	0	0	0	-	-	-	-	4	19	54	1	22
		B -50+70	99	1	0	0	0	0.11	0.04	0.39	0.69	2	18	51	2	27
18	dune sand: 13-23 ft (4-7 m)	A	96	4	0	0	0	-	-	-	-	4	15	48	1	32
		B -50+70	94	6	0	0	0	0.13	0.03	0.37	0.68	4	14	46	0	36
19	dune sand	A	82	10	3	0	5	-	-	-	-	9	18	35	6	32
		B -100+140	82	10	3	0	5	0.39	-	-	-	-	-	-	-	-
20	dune sand	A	63	16	13	0	8	-	-	-	-	8	14	43	1	34
		B -100+140	63	16	13	0	8	0.45	0.04	0.88	1.12	-	-	-	-	-
21	dune sand	A	70	16	6	0	8	-	-	-	-	4	10	62	2	22
		B -100+140	70	16	6	0	8	0.38	-	-	-	-	-	-	-	-
22	dune sand	A	90	6	3	0	1	-	-	-	-	12	16	44	1	27
		B -50+70	88	8	4	0	0	0.34	-	-	-	13	17	42	1	27
23	dune sand	A	90	6	0	0	4	-	-	-	-	2	7	46	2	43
		B -50+70	91	4	0	0	5	0.72	-	-	-	4	6	37	4	49
24	dune sand	A	90	8	2	0	0	-	-	-	-	8	13	46	0	33
		B -70+100	90	7	3	0	0	1.19	-	-	-	9	9	46	0	36
25	dune sand	A	89	9	1	0	1	-	-	-	-	11	24	49	1	12
		B -50+70	89	9	1	0	1	0.56	0.06	1.72	2.16	11	22	56	3	8
26	dune sand	A	86	10	2	0	2	-	-	-	-	4	10	51	0	35
		B -70+100	85	12	2	0	1	0.36	0.03	1.65	2.33	5	8	51	0	36
27	dune sand	A	94	6	0	0	0	-	-	-	-	3	11	38	2	46
		B -70+100	95	5	0	0	0	0.62	0.02	0.69	0.84	2	11	37	2	48
28	dune sand	A	92	7	0	0	1	-	-	-	-	6	27	42	2	23
		B -70+100	94	4	1	1	0	0.53	0.02	1.84	2.10	6	30	37	0	27
29	dune sand	A	93	6	0	0	1	-	-	-	-	15	32	36	1	16
		B -70+100	93	6	0	0	1	0.42	0.04	1.03	1.29	.15	33	40	1	11

*A = Washed bulk sample.
 B = Washed modal size fraction, U.S. Standard Mesh Size (refer to Table 1 for corresponding metric sizes).
 C = Washed glass-grade fraction.

[†] Modal fraction. Also glass-grade fraction for tailings sands only.

[1] Includes magnetic and heavy minerals, rock fragments.

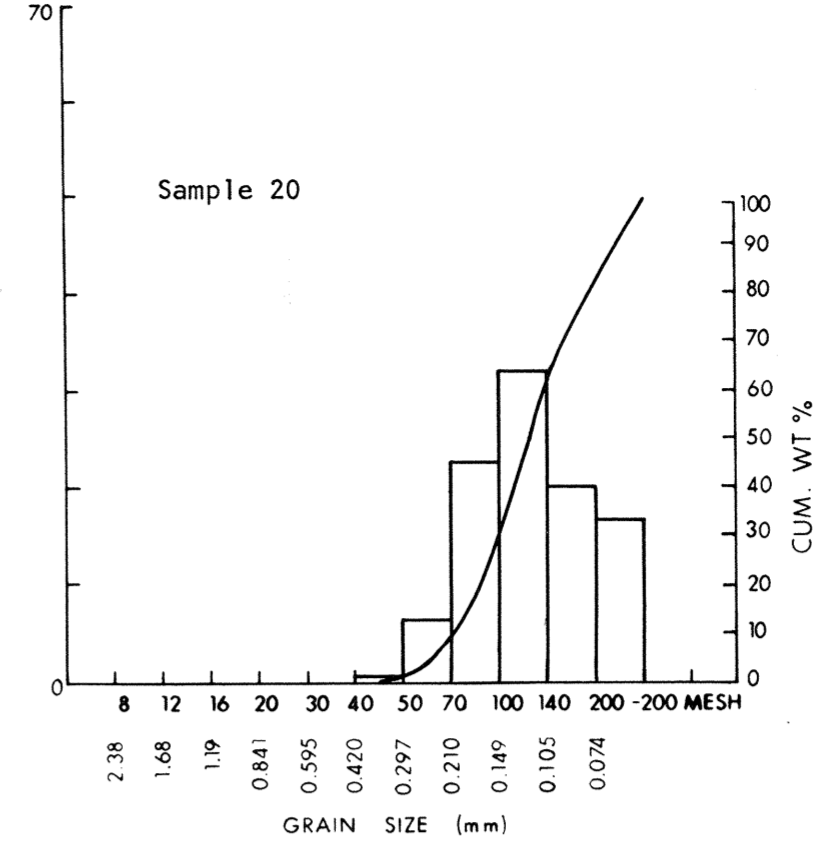[2] Current applied to electromagnet of Franz Isodynamic Separator set at a slope of 18° and a tilt of 10°.

Table 3. Chemical Analyses of Silica Sands from the Fort McMurray Area

Sample Number	Type of Sample		Constituent (Wt. %) SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	MnO	CaO	MgO	Na_2O	K_2O	L.O.I.	Total
1	oil sand tailings (GCOS)	bulk	97.60	1.07	0.18	0.08	0.02	0.00	0.05	0.02	0.00	0.45	0.47	99.94
		modal(4)	98.36	0.89	0.05	0.08	0.01	0.00	0.01	0.01	0.04	0.42	0.29	100.16
2	oil sand tailings (Cities Service)	bulk	97.97	0.81	0.19	0.07	0.02	0.00	0.05	0.01	0.00	0.32	0.34	99.78
		modal(4)	98.74	0.60	0.09	0.04	0.01	0.01	0.00	0.02	0.00	0.28	0.06	99.85
3	oil sand tailings (Abasand)	bulk	97.16	1.01	0.12	0.11	0.02	0.00	0.05	0.01	0.00	0.38	0.23	99.09
		modal(4)	97.83	0.84	0.11	0.10	0.01	0.00	0.00	0.02	0.00	0.40	0.32	99.63
4	oil sand tailings (Bitumount)	bulk	97.53	0.72	0.35	0.05	0.01	0.00	0.17	0.06	0.12	0.39	0.30	99.70
		modal(3)	97.83	0.61	0.26	0.05	0.02	0.00	0.04	0.04	0.03	0.11	0.04	99.03
5	McMurray Formation bedrock sand: 0-10 ft (0-3 m)	bulk	96.38	1.13	0.23	0.15	0.02	0.01	0.12	0.10	0.04	0.60	0.34	99.12
		modal(4)	97.50	1.02	0.08	0.15	0.01	0.00	0.00	0.03	0.00	0.47	0.15	99.41
6	McMurray Formation bedrock sand: 10-30 ft (3-9 m)	bulk	96.15	0.94	0.36	0.14	0.11	0.00	0.08	0.08	0.13	0.69	0.58	99.26
		modal(4)	97.90	0.95	0.08	0.15	0.01	0.00	0.00	0.01	0.00	0.48	0.16	99.74
7	McMurray Formation bedrock sand: 30-45 ft (9-14 m)	bulk	97.31	1.28	0.18	0.08	0.02	0.01	0.08	0.07	0.08	0.79	0.32	100.22
		modal(3)	97.47	1.18	0.07	0.05	0.02	0.01	0.01	0.01	0.00	0.72	0.12	99.65
8	McMurray Formation bedrock sand: 45-60 ft (14-18 m)	bulk	97.10	0.97	0.11	0.09	0.05	0.00	0.16	0.10	0.13	0.74	0.21	99.66
		modal(3)	98.71	0.78	0.04	0.08	0.00	0.01	0.00	0.03	0.00	0.38	0.00	100.03
9	McMurray Formation bedrock sand: 60-63 ft (18-19 m)	bulk	96.73	1.22	0.18	0.13	0.12	0.00	0.14	0.12	0.13	0.89	0.43	100.09
		modal(1)	98.02	0.94	0.07	0.07	0.01	0.00	0.00	0.02	0.00	0.50	0.10	99.73

Testhole 1

Sample Number	Type of Sample		SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	MnO	CaO	MgO	Na_2O	K_2O	L.O.I.	Total
10	alluvial (bedrock channel) sand: 20-40 ft (6-12 m)	bulk	95.68	1.51	0.31	0.07	0.13	0.01	0.23	0.18	0.12	0.29	0.68	99.21
		modal(4)	97.54	1.16	0.15	0.06	0.02	0.00	0.08	0.05	0.14	0.21	0.22	99.63
11	alluvial (bedrock channel) sand: 40-50 ft (12-15 m)	bulk	95.95	1.34	0.29	0.09	0.24	0.01	0.12	0.10	0.20	0.31	0.24	98.89
		modal(5)	97.29	1.38	0.16	0.08	0.02	0.00	0.09	0.05	0.21	0.27	0.20	99.75
12	alluvial (bedrock channel) sand: 50-60 ft (15-18 m)	bulk	95.79	1.78	0.29	0.08	0.13	0.01	0.22	0.15	0.27	0.38	0.32	99.42
		modal(5)	96.01	1.59	0.15	0.07	0.02	0.00	0.18	0.06	0.22	0.30	0.21	98.81

Testhole 2

Sample Number	Type of Sample		SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	MnO	CaO	MgO	Na_2O	K_2O	L.O.I.	Total
13	alluvial (bedrock channel) sand: 20-25 ft (6-8 m)	bulk	96.34	1.39	0.31	0.06	0.12	0.02	0.29	0.18	0.14	0.27	0.53	99.65
		modal(2)	97.79	1.12	0.14	0.06	0.03	0.00	0.08	0.09	0.06	0.17	0.14	99.68
14	alluvial (bedrock channel) sand: 25-45 ft (8-14 m)	bulk	97.23	1.27	0.21	0.06	0.02	0.00	0.31	0.15	0.29	0.30	0.31	100.15
		modal(3)	98.13	1.08	0.13	0.05	0.02	0.00	0.09	0.04	0.14	0.19	0.17	100.04
15	alluvial (bedrock channel) sand: 45-65 ft (14-20 m)	bulk	95.95	1.58	0.30	0.12	0.15	0.01	0.32	0.16	0.26	0.36	0.28	99.49
		modal(2)	97.18	1.47	0.18	0.09	0.02	0.00	0.08	0.07	0.14	0.19	0.11	99.53

Testhole 3

Sample Number	Type of Sample		SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	MnO	CaO	MgO	Na_2O	K_2O	L.O.I.	Total
16	alluvial (bedrock channel) sand: 20-30 ft (6-9 m)	bulk	96.01	1.02	0.29	0.09	0.03	0.00	0.64	0.27	0.21	0.26	0.78	99.60
		modal(3)	98.03	0.90	0.10	0.06	0.02	0.00	0.11	0.03	0.13	0.15	0.14	99.67
17	dune sand: 3-13 ft (1-4 m)	bulk	97.85	0.87	0.14	0.07	0.15	0.01	0.15	0.05	0.10	0.18	0.13	99.70
		modal(3)	98.16	0.94	0.10	0.08	0.03	0.00	0.14	0.07	0.17	0.21	0.18	100.08
18	dune sand: 13-23 ft (4-7 m)	bulk	98.13	0.94	0.12	0.06	0.04	0.01	0.06	0.06	0.02	0.12	0.10	99.66
		modal(3)	98.25	0.71	0.09	0.07	0.02	0.00	0.11	0.05	0.12	0.14	0.14	99.72
19	dune sand	bulk	87.88	5.29	1.26	0.20	0.14	0.03	0.40	0.44	0.92	1.16	1.12	98.84
		modal(5)	89.16	4.81	1.25	0.20	0.05	0.01	0.53	0.34	1.09	1.30	0.96	99.70
20	dune sand	bulk	84.47	6.93	1.59	0.28	0.08	0.03	0.60	0.43	1.29	1.42	1.42	98.54
		modal(5)	85.50	6.48	1.71	0.25	0.09	0.02	0.67	0.42	1.38	1.60	1.27	99.39
21	dune sand	bulk	87.34	5.55	1.45	0.24	0.25	0.01	0.38	0.37	0.92	1.23	1.31	99.05
		modal(5)	90.64	4.60	0.76	0.18	0.12	0.01	0.40	0.26	0.93	1.29	0.57	99.76
22	dune sand	bulk	95.27	1.68	0.47	0.11	0.14	0.01	0.05	0.09	0.10	0.52	0.63	99.07
		modal(3)	95.83	0.70	0.58	0.05	0.04	0.00	0.20	0.09	0.25	0.57	0.43	98.74
23	dune sand	bulk	95.42	1.91	0.49	0.09	0.06	0.01	0.09	0.10	0.12	0.62	0.46	99.37
		modal(3)	96.33	1.84	0.33	0.07	0.02	0.00	0.13	0.03	0.16	0.67	0.25	99.83
24	dune sand	bulk	92.92	3.16	0.66	0.12	0.06	0.02	0.31	0.17	0.57	0.77	0.43	99.19
		modal(4)	93.21	2.90	0.57	0.12	0.03	0.00	0.31	0.12	0.82	0.80	0.40	99.28
25	dune sand	bulk	94.44	2.66	0.52	0.15	0.08	0.01	0.34	0.14	0.48	0.67	0.69	100.18
		modal(3)	95.23	2.19	0.34	0.11	0.03	0.00	0.23	0.07	0.32	0.48	0.41	99.41
26	dune sand	bulk	93.32	3.02	0.73	0.20	0.16	0.01	0.44	0.19	0.45	0.84	0.63	99.99
		modal(4)	95.22	2.34	0.33	0.12	0.03	0.00	0.23	0.08	0.35	0.67	0.33	99.70
27	dune sand	bulk	96.11	1.79	0.49	0.08	0.03	0.00	0.25	0.13	0.22	0.38	0.13	99.61
		modal(4)	97.05	1.53	0.28	0.07	0.03	0.00	0.19	0.06	0.18	0.30	0.30	99.99
28	dune sand	bulk	93.60	2.95	0.59	0.13	0.08	0.02	0.39	0.05	0.56	0.72	0.54	99.63
		modal(4)	95.42	2.31	0.34	0.09	0.02	0.00	0.20	0.55	0.42	0.58	0.32	100.25
29	dune sand	bulk	93.60	2.91	0.60	0.23	0.08	0.01	0.42	0.16	0.55	0.64	0.54	99.74
		modal(4)	95.08	2.60	0.39	0.13	0.05	0.00	0.43	0.09	0.43	0.55	0.45	100.18

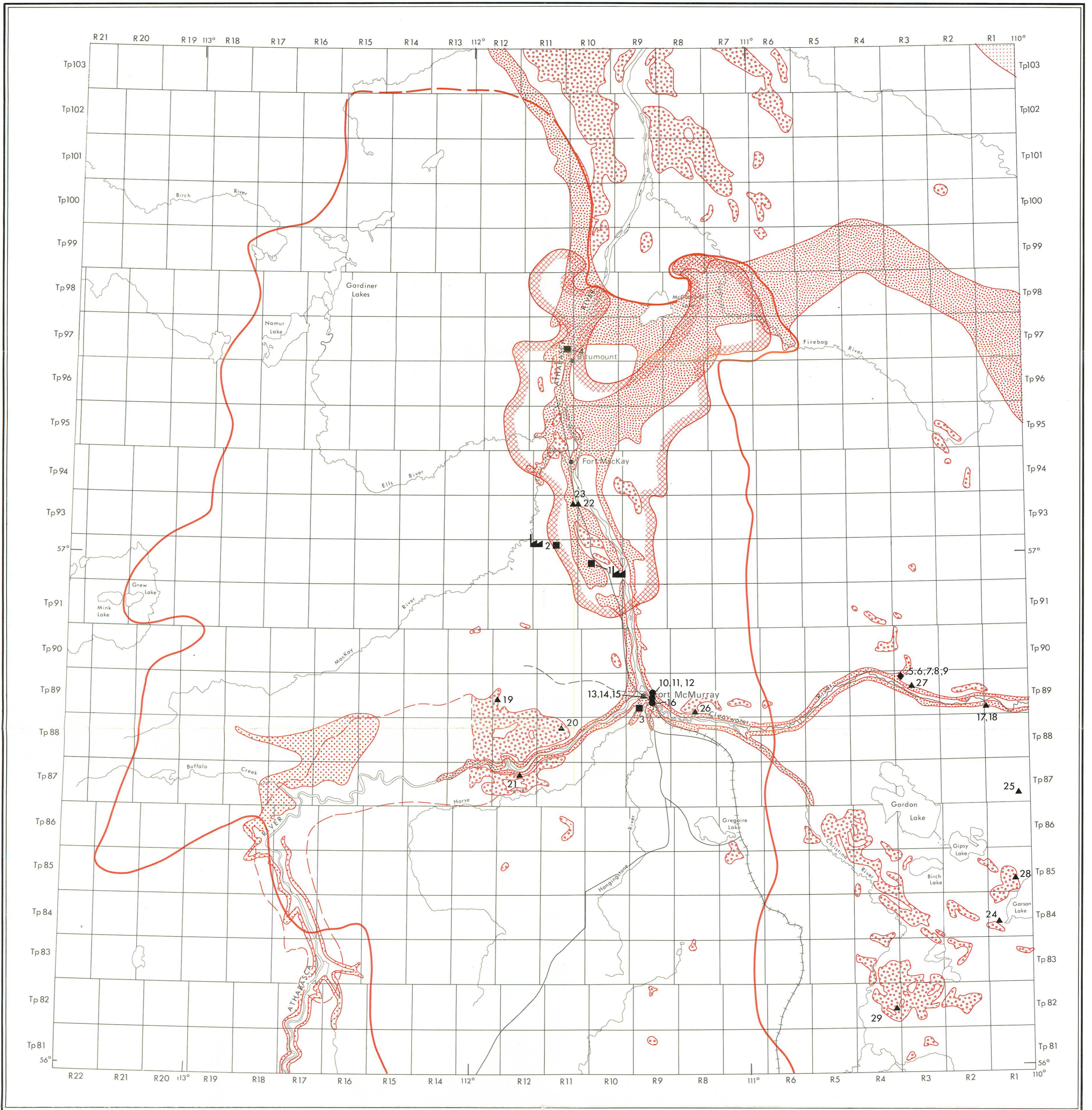Modal size ranges: (1) -20+30; (2) -40+50; (3) -50+70; (4) -70+100; (5) -100+140

Tp103
Tp102
Tp101
Tp100
Tp99
Tp98
Tp97
Tp96
Tp95
Tp94
Tp93
57°
Tp91
Tp90
Tp89
Tp88
Tp87
Tp86
Tp85
Tp84
Tp83
Tp82
Tp81
56°

Birch River
Gardiner Lakes
Namur Lake
Grew Lake
Mink Lake
Buffalo Creek
Ells River
MacKay River
Horse River
Hangingstone River
Christina River
Athabasca River
Clearwater River
Firebag River
Gregoire Lake
Gordon Lake
Gipsy Lake
Birch Lake
Garson Lake

Bitumount
Fort MacKay
Fort McMurray

23 22
2
10,11,12
13,14,15
16
3
26
19
20
21
25
24
28
29
27
17,18
5,6,7,8,9

FIGURE 4. Geology of silica sand sources in the Fort McMurray area, and location of sampling sites

Scale 1:500,000

Miles 5   0   5   10   15   20 Miles

Kilometres 5   0   5   10   15   20   25   30 Kilometres
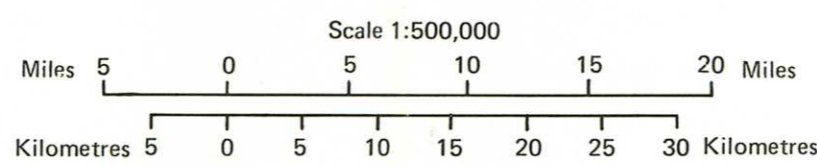
LEGEND

Location of sand dune

defined . . . .

inferred . . . .

Area of outcrop of Pelican Formation . . . .

Area of outcrop of McMurray Formation . . . .

Geological boundary of oil-impregnated McMurray Formation
(Athabasca Oil Sands):

defined . . . .

inferred . . . .

Areas of surface-mineable oil-impregnated McMurray Formation
(Athabasca Oil Sands) . . . .

Area of outcrop of Precambrian Athabasca Formation . . . . .

Location of Great Canadian Oil Sands Ltd. processing plant . . 1

Location of Syncrude Ltd. processing plant 2

Sample location:

tailings sand sample . . . . ■

dune sand sample . . . . ▲

alluvial sand sample . . . . ●

bedrock sample . . . . ◆

Highway . . . .

Dry weather road . . . .

Northern Alberta Railway . . . .

Alberta
RESEARCH COUNCIL