GEOLOGICAL ASPECTS OF SALINE CREEK TUNNEL

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A REPORT

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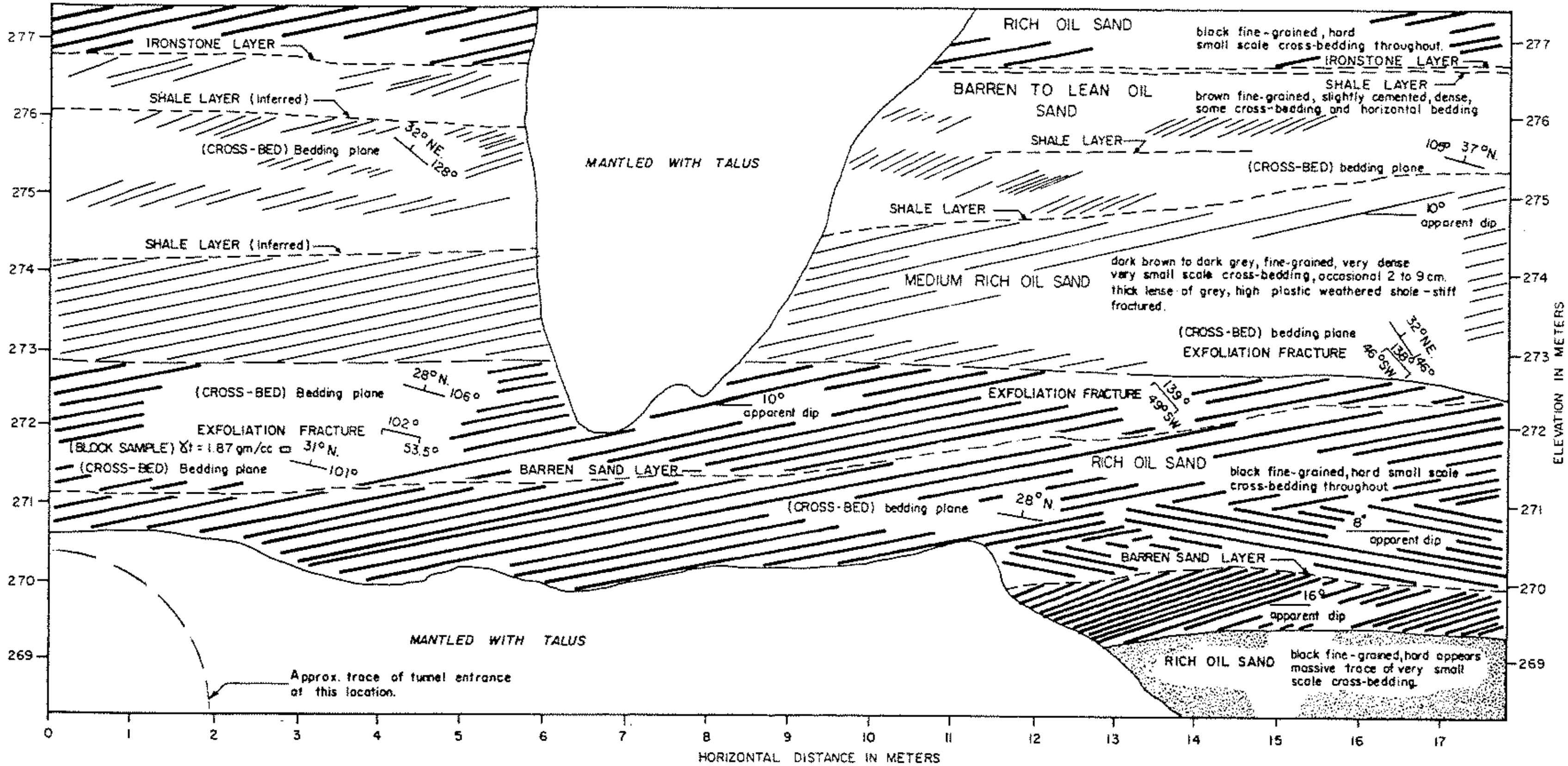

Figure 33 OBLIQUE GEOLOGIC SECTION OF UPSTREAM OUTCROP FACE.

ABSTRACT

The construction of Saline Creek Tunnel within the Athabasca Oil Sands has presented a unique opportunity to study the excavation of a cavity in oil sands. This report presents the results of a geological and geotechnical investigation for the design of the tunnel, along with observations made during construction of the tunnel. The report is limited to the aspects of depositional environment, lithology and the fracture phenomena of the oil sands exposed in the tunnel excavation, along with their predicted and observed effect on the construction procedure and the integrity of the finished tunnel.

A fluviatile environment of deposition was determined from observed features. It was predicted and eventually observed that the tunnel excavation was through rich oil sand exhibiting high-angle cross-beds. It is apparent that reconstruction of the depositional history provides the key to extrapolation of lithology. The lateral extent of the major units as well as the discontinuities was predicted with reasonable accuracy.

A detailed study of the fracture phenomena was carried out on the outcrops at the site and within the tunnel excavation. Exfoliation fractures, sub-parallel to the outcrop face, were the dominant fracture set. These fractures, caused by

stress relief due to valley formation, were observed a maximum of 4.9 meters from the original outcrop face. Cross fractures, perpendicular to the exfoliation fractures, and some partings along cross-bed planes were also observed.

The study serves a useful purpose by successfully applying an analysis of facies change and structural geology to an engineering problem in oil sand. It is intended that the results be considered for applicability to other cavities in oil sand such as open pit and underground mines.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

1.1 The Athabasca Oil Sands

The Athabasca Oil Sands are estimated to contain more than 600 billion barrels of heavy oil (Govier, 1973), representing the world's largest known reserve. Due to recent exploitation of the oil sands through open pit and *in situ* recovery schemes, a great deal of interest in the geotechnical behaviour of oil sands has been generated. Most of the research has been directed toward evaluating the geotechnical properties of the oil sands under conditions of these two mining methods. Open pit mining is feasible where the depth of overburden is less than 50 meters; and, *in situ* recovery appears feasible where the depth of overburden is greater than 200 meters. Very little research has been directed specifically at underground mining techniques (which may prove feasible where depth of overburden is between 50 and 200 meters), partly because interest in this method lags somewhat behind that in the other two, but also because the opportunity to study underground openings has not existed. The construction of Saline Creek Tunnel within the Athabasca Oil Sands has presented a unique opportunity to study the excavation of, and the performance of a cavity in oil sands. The location of the study site is shown relative to the

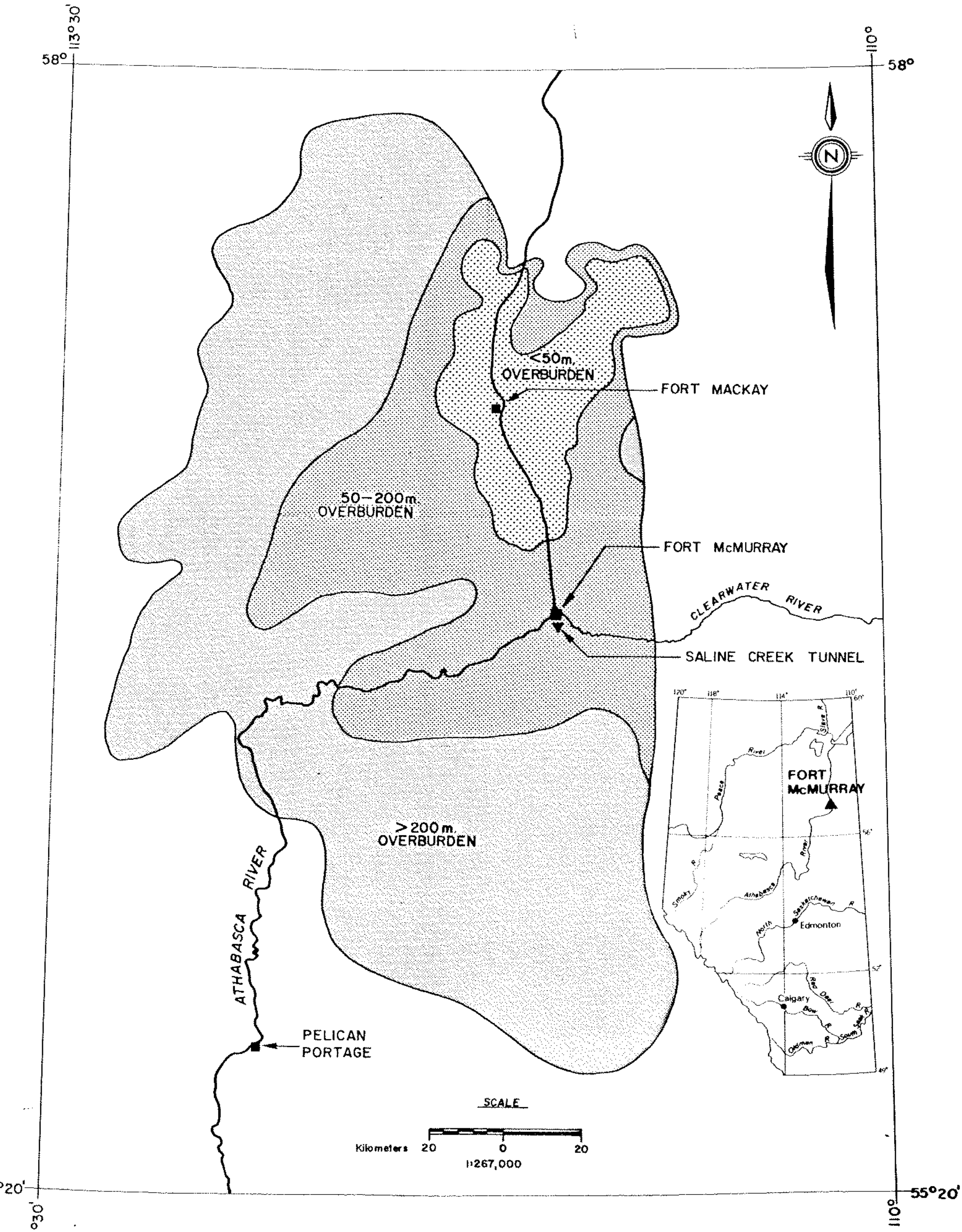


Figure 1.1 THE ATHABASCA OIL SANDS DEPOSIT.

limits of the oil sands deposits and geographical boundaries in Figure 1.1.

Predicting the reaction of oil sands to construction activities, such as blasting of excavations, vehicular traffic, and mining excavation, is a relatively new engineering science. There is a need to document experiences in order to improve our knowledge of the *in situ* properties and to improve our predictive capacity. It is hoped that this report, by documenting geologic predictions made during a site investigation and the observations made during actual construction, will add to our predictive capabilities.

1.2 Scope of the Report

This report presents the results of a geological and geotechnical investigation for the design of Saline Creek Tunnel, along with observations made during construction of the tunnel. Site investigation methods used to predict the behaviour of the material through which the tunnel is excavated, include a literature survey, geologic mapping of exposed outcrop faces, test hole and geophysical logging and laboratory testing of recovered samples. This report is limited to the aspects of geologic history, lithology and the fracture phenomena of the oil sands exposed in the tunnel excavation, and their predicted and observed effect on the construction procedure and the integrity of the finished tunnel. The methods used to observe the nature and performance of the oil sands in the tunnel excavation include:

geologic mapping of the exposed oil sand; examination of samples obtained during excavation of the tunnel; and monitoring of displacement by means of single-point extensometers, multi-point extensometers, slope indicators, and vernier depth gauges.

1.3 Organization of the Report

It is appropriate to first present an overview of the geology of the Athabasca Oil Sands as it is presented in the Literature. Thus, a synthesis of published data is provided, describing the geologic history, lithology and the fracture phenomena observed in the Athabasca Oil Sands deposit. Next the methods employed in, and the results of the geological and geotechnical site investigation for Saline Creek Tunnel are described, along with the predicted geology within the tunnel excavation. A prediction of the depositional environment, lithology and fracture phenomena that would be encountered in the tunnel is presented along with a discussion of the factors that make prediction and extrapolation difficult. Then the geology, as mapped during the actual tunnel excavation, is presented along with a camparison to that predicted in the previous chapter. Conclusions regarding our predictive capabilities in tar sands are presented in the closing remarks.

CHAPTER II

GENERAL GEOLOGY OF THE ATHABASCA OIL SANDS

2.1 Introduction

The depositional history and lithology of the Athabasca Oil Sands have been adequately described in several papers by Carrigy (1959, 1962, 1963a, 1963b, 1966, 1967, 1971, 1973a & 1973b). Studies of fracture phenomena in this region are presented in Babcock (1975), Babcock and Sheldon (1976) and Dusseault (1977). This chapter of the report attempts only to synthesize the data accumulated in these papers.

The Athabasca Oil Sands are a large oil-bearing sedimentary deposit in northeastern Alberta. The extent of the reservoir is illustrated in Figure 2.1. The heavy oil is found in Lower Cretaceous strata (McMurray and Clearwater Formations) which unconformably overly Devonian (Waterways Formation) limestones. The simplified stratigraphy in the Athabasca Oil Sands area is shown in Figure 2.2.

During the long time gap between Devonian and Lower Cretaceous deposition, the Devonian limestones were probably subjected to several periods of subaerial erosion. Further, depressions had formed on the Upper Devonian beds, where they had collapsed into cavities formed by solution and removal of underlying salt beds (Elk Point Evaporites). The two factors have resulted in a pre-Cretaceous erosion surface with a generally undulating topography and some individual

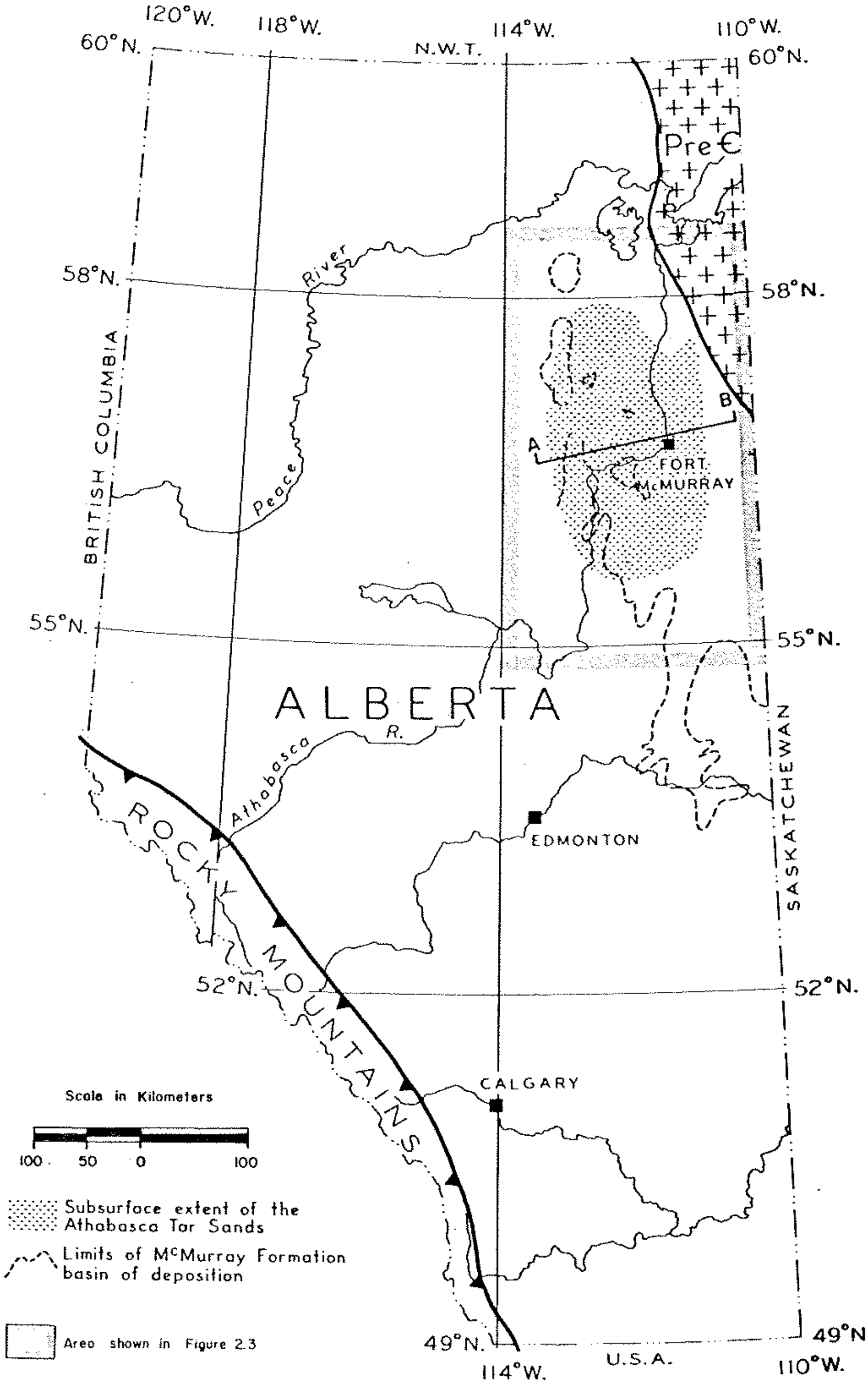
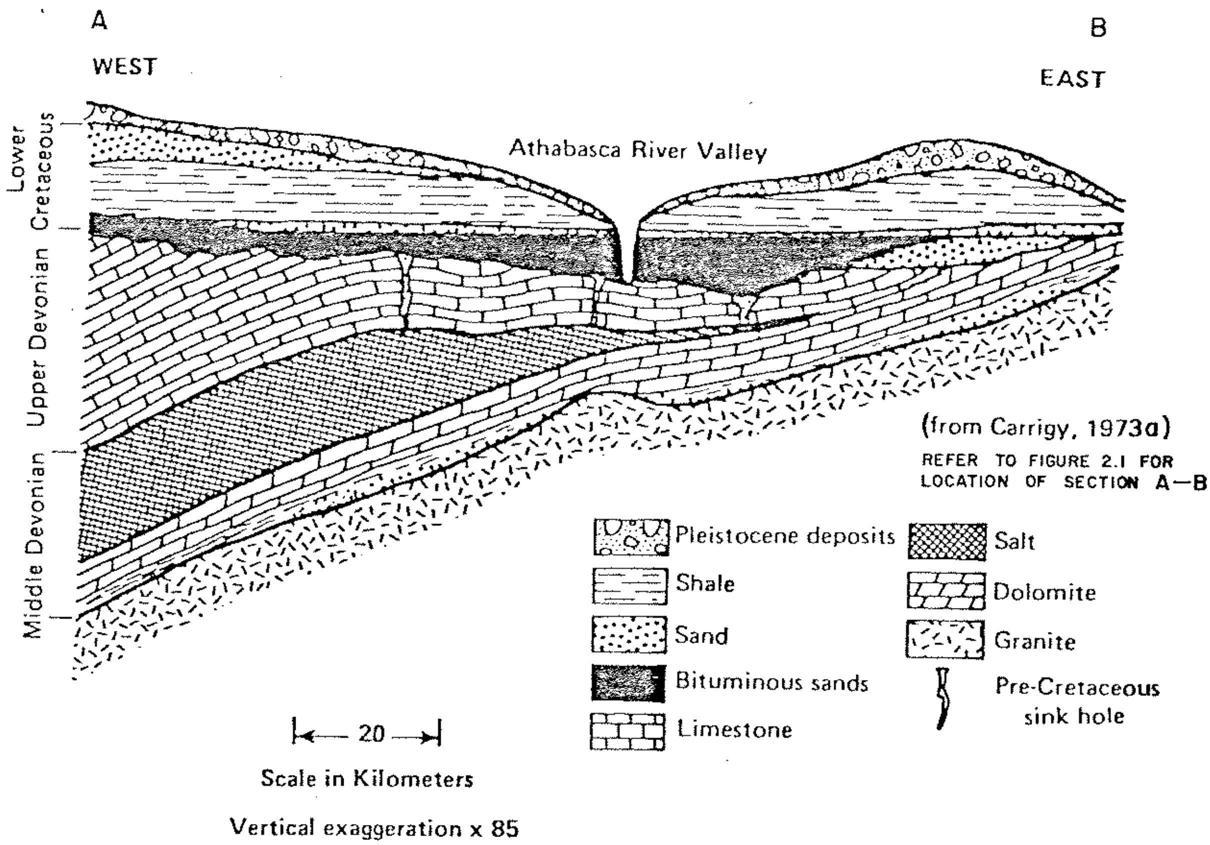


Figure 2.1 INDEX MAP OF ALBERTA (from Carrigy, 1971.)



Formations	Age (millions of years)[1)]	Period	Rock Type
Unnamed Laurentide drift and postglacial sediments	0	Quaternary (Pleistocene)	Glacial till, proglacial lake sediments, aeolian sand
Joli Fou Fmn.	~1.5 ~100	(Post-Cretaceous erosion surface)	Shale
Grand Rapids Fmn.			Sandstone
Clearwater Fmn.		Lower Cretaceous	Shale to fine-grained sand at base
Wabiskaw Mem. McMurray Fmn.			Sand to basal pebble conglomerate, largely uncemented
Waterways	~106 ~360	(Pre-Cretaceous erosion surface) Upper Devonian	Limestones and dolomites
Elk Point		Middle Devonian	Shale, anhydrite salt, dolomite
Unnamed Plutonic rocks	~370 ~1800?	(Pre-Devonian erosion surface) Aphebian (Pre-Cambrian)	Granites, gneisses, Granites, gneisses, schists

(From Geology and Economic Minerals of Canada, 1970.)

Figure 2.2 STRATIGRAPHY OF THE ATHABASCA OIL SANDS. (from Dusseault, 1977) depressions, most notably the Bitumount basin, north of the present Fort McMurray. This left a well-defined drainage system developed on the Upper Devonian surface, prior to deposition of the McMurray and Clearwater Formations in Early Cretaceous time. The approximate configuration of the pre-McMurray drainage system is illustrated in Figure 2.3a (Carrigy, 1973b). This drainage system likely controlled the distribution of the McMurray Formation and in part the oil contained within it.

The McMurray Formation is generally considered to consist of three different lithologic units (Lower, Middle and Upper), each somewhat related to a characteristic environment of deposition. These, along with the depositional environment of the lower Clearwater Formation (which is also oil-impregnated) are illustrated in Figure 2.3. A hypothetical geologic cross-section, which illustrates the stratigraphy that results from the changing depositional environment, is shown in Figure 2.4. Table 2.1 is a summary of the features of the major rock units of the Athabasca Oil Sands.

2.2 Lithology and Depositional Environment

2.2.1 Lower McMurray Formation

Carrigy (1967) suggests that the pattern of internal drainage shown in Figure 2.3a was probably produced by the gradual disruption of a single drainage basin into 2 areas of subsurface drainage, leaving a minor watershed in the vicinity of the town of Fort McMurray. The smaller, northerly basin drained underground into the Bitumount collapse area, and the larger southern basin had its outlet in a sink on the Alberta-Saskatchewan border, at about 56°N. The drainage channels shown on this map commonly contain coarse-grained sands and conglomerate. Some of these sediments may be pre-McMurray in age. The basal strata of the lower McMurray Formation are residual clays derived from weathered Waterways limestones. These are overlain by sediments controlled by the topography. These sediments are coarse-grained sands containing wood fragments, well-rounded quartz grains, feldspar cleavage fragments, and small amounts of mica. In some locations the sand has been found to be barren and contain only fresh water, and in others it is richly impregnated with heavy oil. These sands are interbedded with gray micaceous siltstones.

2.2.2 Middle McMurray Formation

During middle McMurray time it is suggested that a major stream was flowing from the south and east, building a delta across a shallow lake or lagoon, as shown in Figure 2.3b. The concept of a northward flowing river system is supported by the analysis of the cross-stratification in the lower and middle parts of the McMurray Formation (Carrigy, 1963b). Carrigy (1967) surmises that as the sea level rose, the lake in turn became a brackish water lagoon, then a restricted bay, and finally open sea.

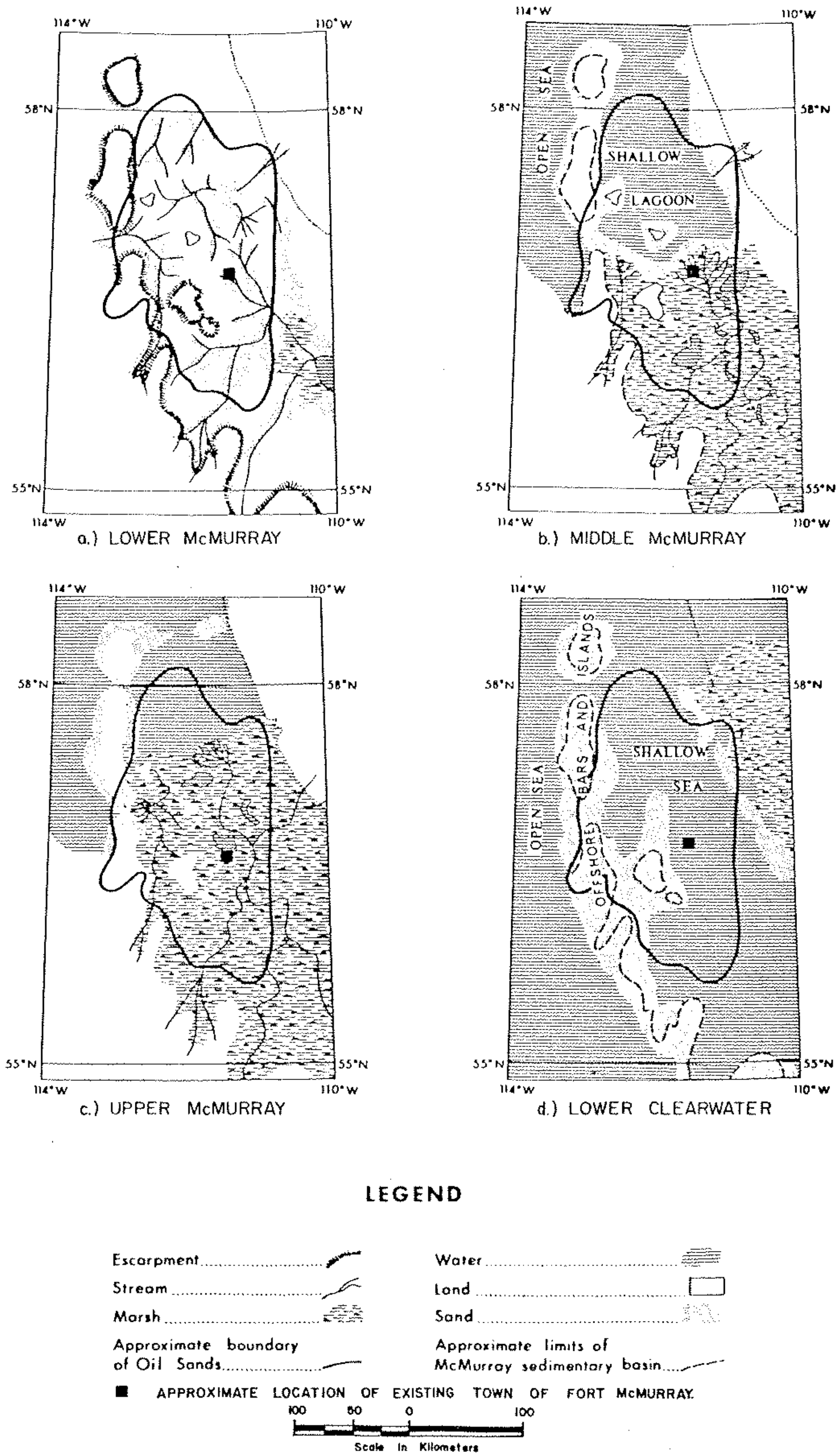


FIGURE 2.3 DEPOSITIONAL ENVIRONMENTS OF THE McMURRAY FORMATION. (from Carrigy, 1971.)

The middle McMurray Formation generally consists of the lower section of fluviatile medium-grained sand occurring in lenticular beds made up of sets of high-angle cross-beds 20-30 cm thick, typically overlain by fine-grained sand of deltaic origin found in large scale, low-angle foreset beds 10-15 cm thick, separated by thin silt laminae a few millimeters thick. The middle McMurray Formation generally lies between elevations 229 and 287 m and is the so-called typical McMurray Formation. It generally has rich uniform oil impregnation. The oil sand beds are often interbedded with lenticular beds of micaceous silts, shales and, in places clay. Also, plant remains, worm casts, logs of wood, and thin coal beds occur in middle McMurray Formation sediments.

2.2.3 Upper McMurray Formation

The upper part of the McMurray Formation is not everywhere clearly differentiated from the middle member. It represents the final stage in the burial of the pre-McMurray depression as shown in Figure 2.3c. At that time, the Devonian strata were covered except for the highest hills and the delta had reached the margin of the open boreal sea to the north. The lithology consists generally of horizontal beds of silt and very fine sand. The sand layers are generally oil impregnated. These beds were likely formed on delta platforms, mudflats, bays and lagoons in a shallow depth of brackish water (Mellon and Wall, 1956). Large shallow channels or scours, filled with silt beds and siderite-

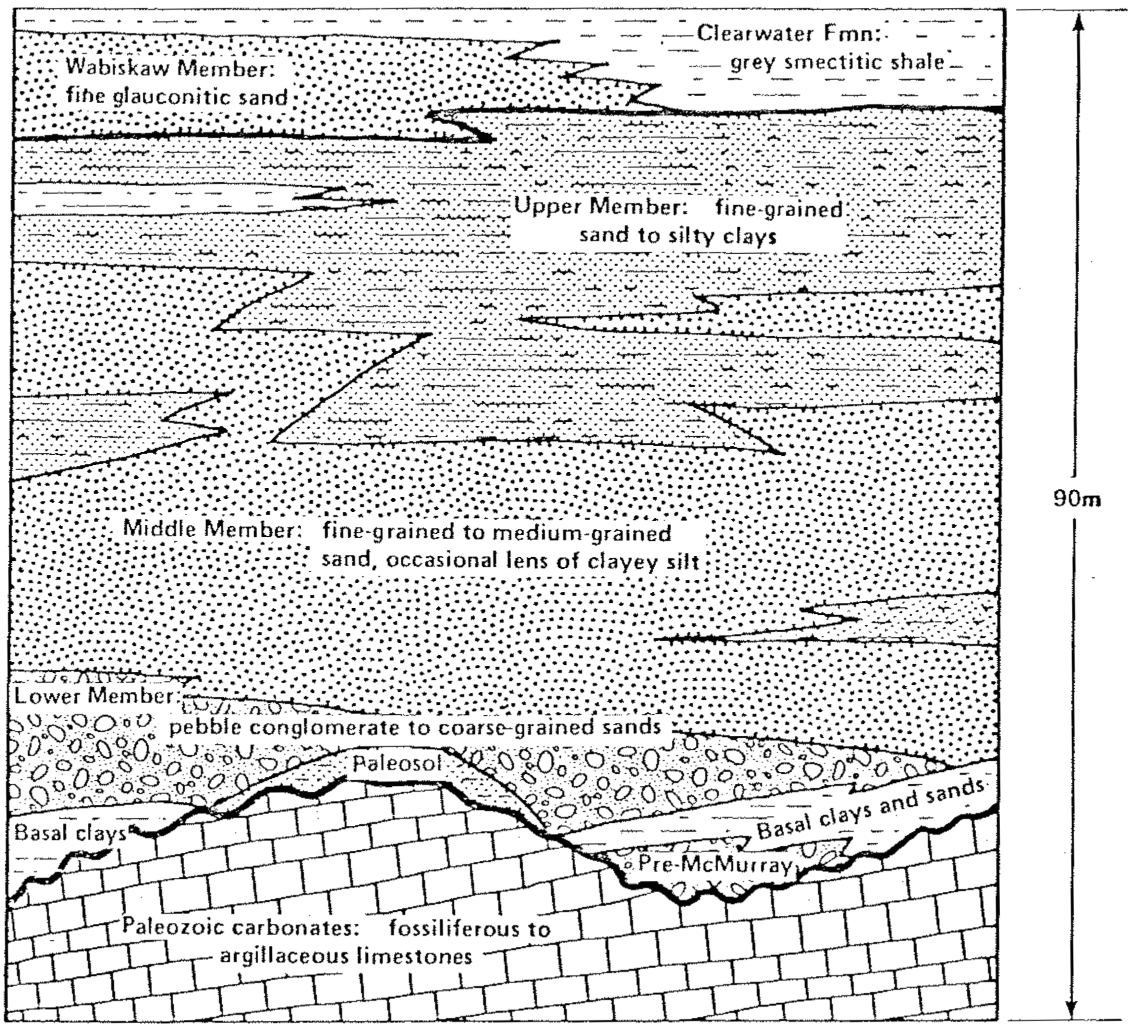


Figure 2.4 HYPOTHETICAL McMURRAY – CLEARWATER FORMATION CROSS-SECTION.
(from Dusseault, 1977)

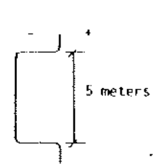
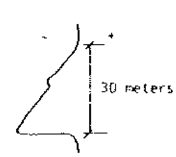
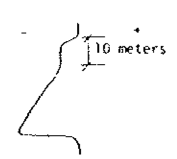
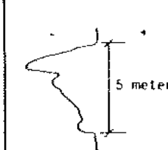
ROCK UNIT	LOWER McMURRAY	MIDDLE McMURRAY		UPPER McMURRAY	CLEARWATER WABISKAW
Environment of Deposition	Fluviatile	Fluviatile	Deltaic Lacustrine	Deltaic Lagoonal	Marine
Types of Deposit	Channel, flood plain and swamp deposits	Point bar and channel sands	Deltaic Foresets	Subaqueous topsets	Barrier bar
Texture	Coarse sand, silt, clay	Medium- to coarse-grained well-sorted sand	Very fine- to fine-grained well-sorted sand	Silt and very fine-grained sand	Sand, silt and clay poorly sorted Locally clean and well-sorted
Sand composition	Quartzite Quartz K-feldspar	Quartz ≈ 95% K-feldspar < 5% Muscovite <1%	Quartz ≈ 90% K-feldspar < 5% Muscovite <5%	Quartz ≈ 90% K-feldspar <5% Muscovite <5%	Quartz ≈ 50% Chert and volcanic rock fragments ≈ 25% Glauconite ≈ 20% Feldspar ≈ 5%
Clay composition	Kaolinite Illite	Kaolinite, Illite	Kaolinite, Illite	Kaolinite, Illite, Montmorillonite	Montmorillonite, Illite, Kaolinite, Chlorite
Organic matter	Autochthonous coal seams Lignite Carbon	Mummified logs, abundant comminuted carbon Some thin coal and lignite beds present	Abundant comminuted carbon	Macerated vegetable matter in clay matrix	
Mineral cements	Siderite	Siderite (rare) Pyrite nodules (rare) (up to 15 cms. diam.)	Siderite (rare)	Siderite (common) and calcite	Siderite (common)
Fossil content	Negligible	Spores and pollen	Spores and pollen	Some lenticular beds of brackish water gastropods and pelecypods Agglutinated foraminifera Pollen and spores Hystrichospherids	Calcareous foraminifera Radiolaria (pyritized) Hystrichospherids Diatoms & Sponge spicules (pyritized)
Sedimentary structures		Medium scale (25 cms), straight, high-angle, cross beds (common)	Large scale (30 meters), low-angle (5-7°), foreset beds Small scale, micro-cross-lamination Burrows and castings (common)	Lenticular sand layers in silt Crab? burrows (rare)	Horizontal and vertical tubes filled with clean white sand
Bedding	Lenticular beds of gravel and gritty beds	Lenticular cosets of cross stratified sets	Silt beds (1 cm thick) interbedded with very fine-grained sand beds (10 cm thick)	Laminated micaceous silt with lenticles of sand	Bedding destroyed by animal activity
Boundaries	Upper and lower boundaries sharp	Upper and lower boundaries sharp	Lower boundary sharp, upper boundary transitional	Upper and lower boundaries transitional	Upper boundary sharp, lower boundary transitional
Thickness	0 - 17 meters	2 - 7 meters	20 - 30 meters	5 - 10 meters	2 - 10 meters
Ideal S.P. response					
Location	Lower one third of the McMurray Formation	Lower one third of the McMurray Formation	Lower two thirds of the McMurray Formation	Upper one third of the McMurray Formation	Basal Clearwater Formation
Oil content	Rich, but variable (up to 35% by volume)	Rich uniform (20 - 30% by volume)	Rich uniform (20 - 30% by volume)	Lean (5 - 10% by volume)	Very lean, variable (local bodies of rich tar sand)

Table 2.1 FEATURES OF DEPOSITIONAL ENVIRONMENTS IN THE ATHABASCA OIL SANDS. (from CARRIGY, 1971 & 1973b)

cemented siltstones, are present.

2.2.4 Lower Clearwater Formation

Figure 2.3d illustrates the early stages of the Clearwater marine transgression. This environment has produced clean well-sorted glauconitic sand. There is a sharp change from the upper McMurray brackish water sands to the Clearwater glauconitic sands, indicating marine sediments and the slowing down of sedimentation. In some areas the sand is shaley or clayey. The average thickness of the sand is 6 m. Grey Clearwater shale overlies the glauconitic sand. The sand is richly impregnated with oil in some locations and represents the upper limit of the Athabasca Oil Sands.

2.3 Fracture Phenomena

Babcock (1975) has condluded that the Devonian Waterways limestone of the Fort McMurray area is fractured by two orthogonal regional joint systems.

Regional joints, although seldom observed, do exist in the McMurray Formation in ironstone beds and at manmade outcrops distant from steep scarps in the oil sands. There is one orthogonal joint system in the McMurray Formation, with set strikes of approximately northeast and northwest, paralelling one of the systems observed in the underlying Waterways limestone. The regional joints in the oil sands will likely conduct flow of injected fluids during *in situ* heavy oil recovery.

Exfoliation fractures were observed at most outcrops and in excavations in the oil sands (Babcock, 1975). These fractures generally have a strike and dip sub-parallel to that of the outcrop face. They are caused by release of lateral confining stress as river valleys or excavations cut down rapidly. These fractures result in spalling of slabs of oil sand, particularly where a river erodes the toe of the slope. The distance to which the exfoliation fractures penetrate the outcrop faces has not been determined.

Cross fractures, striking perpendicular to the outcrop face, were also observed at most outcrops visited during the study described by Babcock (1975). These result from lateral expansion of the exfoliation sheets as they separate from the outcrop face. These fractures will probably be confined to the outermost exfoliation sheets of the oil sands.

Dusseault (1977) reports that the slope angles of fine-grained oil-free to oil-poor portions of exposed natural slopes generally approach the angle of repose of loose granular material, that is, 30 degrees to 35 degrees. Fine-grained oil-rich slopes are generally steeper, varying from 35 degrees to 75 degrees over short sections. However, it was found that within the coarse-grained McMurray sands, bitumen saturation has little or no effect on the slope angles, as both oil-free and oil-rich coarse sands were found in slopes standing at angles as high as 75°. This phenomenon is attributed to the fact that the fine-grained oil-free material has a high capillary suction, and therefore retains more groundwater and is susceptible to degradation of grain fabric by freeze-thaw strains. The other cases (again, fine-grained oil-rich, coarse-grained oil-rich and oil-poor) are well-drained and have low capillarity and therefore retain their high in situ strength that is attributed to diagenetic "locking" of the sand grains.

Dusseault has concluded that exfoliation fractures are the dominant factor affecting slope morphology, usually obscuring the affects of regional joints and the lithological variables of grain size and bedding; however, on active slopes (where debris removal forces are maximized), coarse-grained sands lie at somewhat steeper angles. Dusseault has attributed exfoliation fractures to the rotation of the stress field near a rapidly excavated slope face in a material with high horizontal stress (high K_o), so that the major principle compressive stress lies sub-parallel to the slope face and is much higher than the minor principle compressive stress. If the obliquity is high enough or if the slope face experiences tensile stresses such as those caused by gas expansion pressures, a joint set may develop sub-parallel to the dominant slope face. The exfoliation fractures (stress relief joints) promote slabbing on slope faces where debris removal agents act at the toe of the slope. Slabbing is also promoted by thermal expansion and contraction due to freezing and thawing of water in the joints, gas expansion pressure in the gas-filled voids in the slope (which increases when the slope is heated), and impeded diffusion of gases due to low permeability of the oil sand.

Dusseault (1977) has also presented observations of a hydrogeological nature, made on a number of natural oil sand slopes. Minor surface groundwater seeps on active oil sand slopes are common but their greatly increased rate of occurrence after rainfall suggests that they are solely of surface or near-surface origin. Rainwater and surface meltwater percolate into exfoliation fractures in the surface of the backslopes. This water is released gradually along oil-free or oil-poor seams, resulting in the surface dampness observed. The consistent association of seeps and zones of low oil content indicates that rich oil sand, because of its very low permeability, forms a barrier to water flow, at least at and near the outcrop surfaces. Dusseault has hypothesized that, on a regional basis, the presence of oil sands may result in a perched water table on the upper surface. The base of the oil sands may be free-draining where it consists of jointed limestone, coarse-grained oil-free sands, and pebble conglomerates. On the other hand, where lenticular basal clays occur in the McMurray Formation, the base of the oil sands may not be free-draining and would be difficult to de-pressurize (Morgenstern, 1977).

CHAPTER III

GEOTECHNICAL INVESTIGATION FOR SALINE CREEK TUNNEL

3.1 Introduction

Saline Creek presently flows northward and parallel to Highway 63 near the southern limit of Fort McMurray, as shown on Figure 3.1. A tunnel has been designed to divert the creek flow in order to eliminate the continuing erosion at the toe of a landslide (Slide 1) that may threaten the integrity of the highway. The tunnel would be constructed through an oil sand hill that presently forms the east bank of the creek. Eventually, a stabilizing berm would be placed over the existing creek bed. The results of the investigation and the design of Saline Creek Tunnel were presented in a report to Alberta Transportation by Thurber Consultants Ltd. (1976).

The field investigation for the design of the tunnel consisted of geologic mapping of the exposed outcrop faces, and drilling and geophysical logging near the tunnel alignment. Laboratory testing consisted of visual examination of all core samples and measurement of bulk density on a selected number of samples of oil sands. Unconfined compression tests were carried out on a selected number of samples from at or near the elevation of the proposed tunnel. A summary of the results of the field and laboratory geological investigation is presented in Figure 3.2.

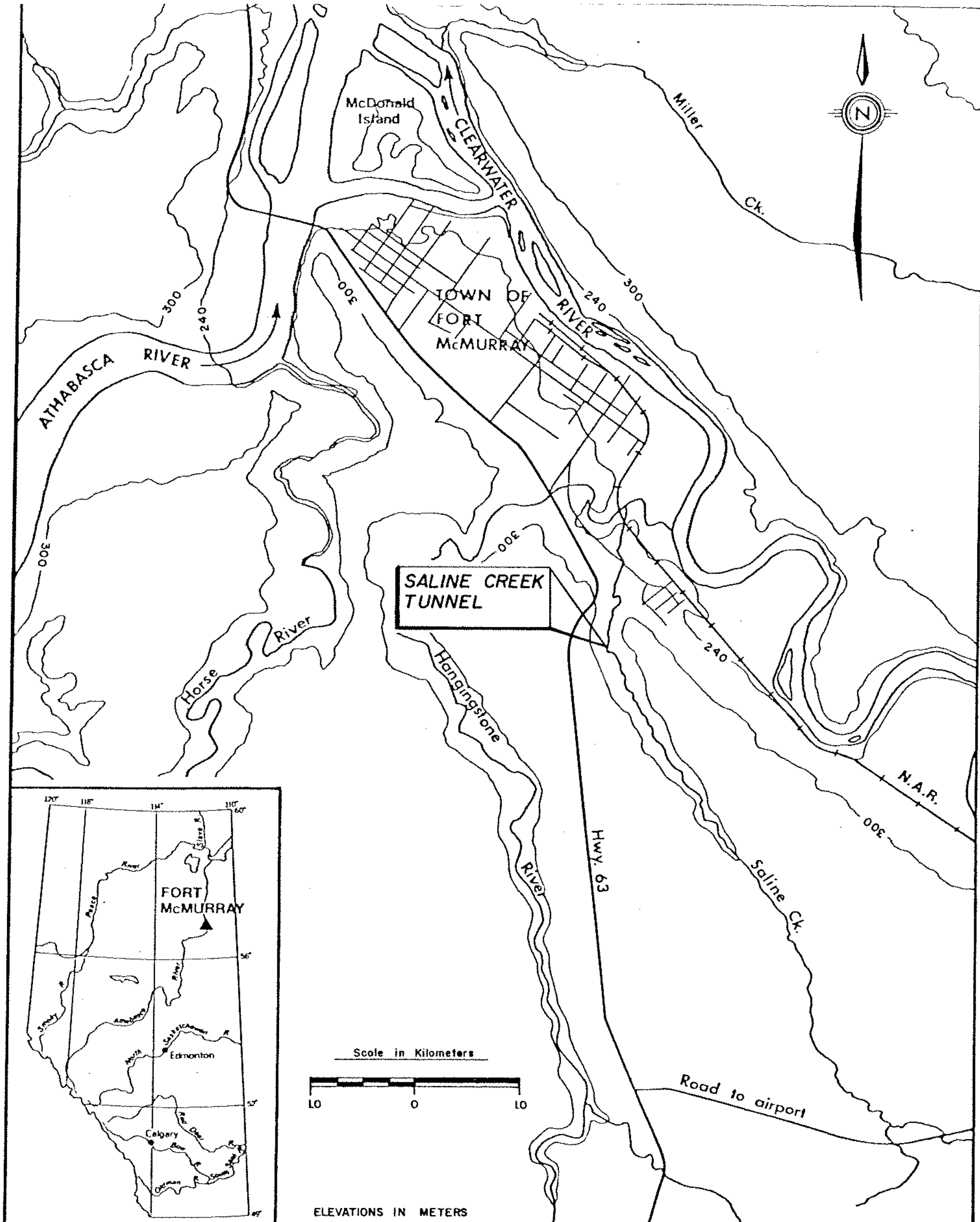


Figure 3.1 LOCATION MAP OF SALINE CREEK TUNNEL.

3.2 Lithology and Depositional Environment

3.2.1 Geologic Mapping Results

Outcrops were accessible for mapping on both the entrance and exit faces of the oil sand hill from approximately the elevation of the spring line of the proposed tunnel to well above the crown of the proposed tunnel. Only the outer few centimeters of bedrock could be mapped; therefore, unweathered or unaltered material could not be observed in most areas of the oil sand hill. Some areas were mantled with talus, obviating direct observation. The lower 27 m of the exposed surface consists of beds of the McMurray Formation. Above these lie the beds of the Clearwater Formation. Only the lower 2 m of the Clearwater Formation was exposed, as the rocks above were mantled with talus and glacial drift. Detailed mapping was carried out for one area of the rock face near the upstream entrance of the proposed tunnel. The results are presented as an oblique section on Figure 3.3.

The elevation of the crown of the proposed tunnel was estimated to be about 270.7 m at the upstream and 268.8 m at the downstream end.

Within the vertical depth of the proposed tunnel excavation two distinct layers were observed in outcrop. The lower layer consists of rich, fine-grained oil sand. Although some thin cross-beds were observed in this layer, the appearance is generally massive and the rock tended not to break along bedding planes. Exfoliation fractures oriented sub-parallel to the rock face and some cross-fractures at random orientations but perpendicular to the rock face appear on the outer surface of this bed. On the north face (downstream face) of the oil sand hill, the top of this "massive" bed is marked by a thin undulating ironstone bed with a top surface of soft clayey siltstone. There were also some small ironstone and siltstone clasts observed within this layer. The massive layer was visible vertically from about creek level, or elevation 268.2 m at the tunnel entrance, up to elevation 269.1 m.

Above the massive bed, a layer of cross-bedded, rich, fine-grained oil sand was observed from elevation 269.1 m up to 272.5 m, thereby forming the roof of the proposed tunnel for most of its length. This layer as a whole appears very competent in weathered outcrops. A few, very thin, less competent barren sand layers and coal seams were observed within this layer, the most conspicuous being at elevation 269.7 m (upstream face only). The exfoliation and cross fractures were observed in this layer, also. The mean orientation of the cross-beds was measured to be: strike 101°, and dip 27.78°N. The cross-beds occur in lenticular 30-centimeter thick sets of high-angle cross-beds, the lower surface of which appears to be a scour surface in some cases. Some clasts were also observed in this layer.

The lithology of the layers observed above elevation

272.5 m is adequately described on the cross-section (Figure 3.2). It consists of layers of McMurray Formation oil sand up to about elevation 292.6 m, above which is found the green glauconitic sand of the Wabiskaw member of the Clearwater Formation. From 272.5 to 293.8 the oil sands vary in oil content from barren to medium rich, and are generally cross-bedded below elevation 284.4 and horizontally bedded above that. Numerous shale and ironstone layers were observed in this section. The McMurray Formation exhibited exfoliation fractures sub-parallel to the outcrop face in this section also.

3.2.2 Drilling Results

Two test holes were drilled and cored from the top of the oil sand hill. Test hole 76-66 was drilled about 12 m east and 76-67 was drilled about 18 m east of the centre of the proposed tunnel. The logs of the holes, along with geophysical logs of holes drilled adjacent to the cored holes are shown in detail in Figure 3.4. Summarized logs are shown on the cross-section (Figure 3.2), for correlation with the geologic mapping and in order to illustrate the probable stratigraphy in the lower half of and below the tunnel, which was not exposed in outcrop.

The general stratigraphy encountered in the test holes correlated well with that mapped in the outcrops. Within the depth of the proposed tunnel excavation (elevation 270.1 to 265.2 near the test holes), rich oil sand interbedded with mainly medium rich oil sand was encountered above about elevation 268.2. This material exhibited high-angle cross-bedding throughout and the core tended to break along the cross-beds (average dip of about 30°). Below elevation 268.2, to about 264.6 m, the material was rich oil sand that exhibited high-angle cross-bedding but had a general tendency to fracture across the bedding planes and along the core axis. This bed appeared to be very similar to the "massive" bed identified in the outcrops.

Thin brownish-grey silty shale layers were observed at about elevation 268.5 and 265.8 m in test hole 76-67. These elevations represent approximately the mid-height and the invert of the tunnel excavation. From elevation 264.6 to 262.1, rich cross-bedded oil sand with several thin shale layers was encountered, underlain by alternating shale and oil sand beds to an elevation of about 256.

The main difference between the oil sand in the cores and that observed in the outcrops is that the outcrop rock has been highly weathered and "case-hardened"*; whereas, the cores are very fresh. The cross-beds and any other sedimentary structures are generally more visible in the outcrops as the high oil saturation in fresh cores tends to

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*Dusseault (1977), p. 54, found that the weathered bitumen in the outer layer of outcrops has a higher viscosity than typical unweathered bitumen. He suggests that "case-hardening" may be the result of weathered bitumen acting as a true cementing agent; whereas, he has shown that the unweathered bitumen does not act as a true cementing agent.

obscure such features. Conversely, less competent materials such as clay, coal and barren, uncemented sand tend to be absent in weathered outcrops and can be observed in the cores.

3.2.3 Geophysical Logging Results

As previously mentioned, holes were drilled adjacent to each test hole and downhole geophysical logging was carried out in each. The geophysical methods employed include the following:

1) Focused beam resistivity logs indicated oil content and helped confirm stratigraphy.
2) Gamma logs indicated clay content and helped confirm stratigraphy.
3) Sidewall Gamma - Gamma Densilog measured bulk density.
4) Caliper runs measured test hole diameter.

The average resistivity was fairly high, 375 ohm-meters over the interval of the tunnel, indicating rich oil sand. The average porosity was estimated to be about 33% and the oil content of the porosity, about 72% by volume. Therefore, the oil content would be about 23.8% by volume. The resistivity curve was variable on a local scale but indicated a uniform trend over the large interval.

The gamma-ray log curve was uniform from elevation 273.7 to about 262.7 m, indicating a low uniform clay content of about 12% within the depth of the proposed tunnel excavation.

The bulk density measurement taken shortly after drilling indicated a fairly uniform value of about 2.1 gm/cc through the depth of the proposed tunnel except near the top and bottom in test hole 76-67. At these two elevations, very low densities were measured, indicating that gas may have been released quickly due to release of in situ stresses by the drilling and removal of the core, causing expansion and reduced density. The bulk density actually increased with time after the earlier descrease, indicating that oil or water may have moved into the voids created by expanded gas that may have escaped, thereby increasing the density. The remainder of the interval showed little or no variation in density with time.

The caliper runs indicated that the sides of the hole squeezed in slightly with time between elevations 275.8 and 271.3 in test hole 76-67, indicating that the oil sand did expand with time in this interval, which is just above the tunnel excavation.

3.2.4 Laboratory Testing Results

Bulk density did actually decrease with time on core samples on which tests were carried out in the field and laboratory from within the interval 275.8 to 271.3 in test hole 76-67, just above the tunnel. The average density dropped from 2.02 gm/cc to 1.95 gm/cc in one week.

Unconfined compressive strength tests were carried out on selected samples. All samples likely were disturbed to some degree. Although the test results are not considered to be indicative of *in situ* strength, it can be concluded that the oil sand tested was a high strength material.

3.2.5 Interpretation and Discussion

In order to adequately assess the economic value of an oil reservoir, exploration must define the lateral distribution of the potential reservoir rock. Determination of the environment of deposition is the key to extrapolation of lithology. Geotechnical engineering concerns, with respect to surface and underground mining of oil sands, emcompass both the extent of the reservoir rock as well as the continuity of materials that may be detrimental to the mining process.

It is necessary to determine the sequence of depositional environments represented in a particular section and the direction in which the sediment was carried and deposited. Carrigy (1971) notes that "one of the outstanding features of the McMurray Formation is the absence of correlatable units within the formation. The nature of the reservoir boundary is difficult to determine because of the lensing nature of the sandstone bodies". Ansley and Bierlmeier (1963) experienced difficulty in tracing thin beds in drill holes at 61-meter centres.

The sequence of environments under which the McMurray and Lower Clearwater sediments were deposited are described along with their associated lithologies and sedimentary features in Chapter II of this report. These are summarized in Table 2.1.

An examination of the observations from the Saline Creek Tunnel site indicated that the tunnel excavation would likely be carried through rich, fine- to medium-grained oil sand deposited in a fluviatile environment, corresponding to Carrigy's (1973) lower section of middle McMurray, called point bar deposition. This is simply an early stage in the overall valley-fill cycle (Visher, 1965).

The valley-fill deposits are generated by the lateral migration of a stream within a fluvial valley. Point bars are deposited by lateral accretion on the inside of a meander. Therefore, the entire section from the base of the channel to the floodplain is deposited simultaneously. This is supported by the poorly graded (well-sorted) sand gradation observed in outcrop, test hole cores and geophysical logs from about elevation 262.7 to 273.7 m. This zone is also characterized by lenticular sets of high-angle cross-beds. The dip direction of the cross-beds generally varies up to about 180° around a mean value that closely represents the regional slope direction of the fluvial valley. Large local variations in the dip direction are primarily due to the migration of the transverse sand bars in the meandering (or possibly braided) rivers in which the cross-beds were formed. The vector mean direction of dip azimuths for many high-angle planar cross-beds throughout the McMurray Formation measured by Carrigy (1963b) is 350 degrees and a similar mean direction was found for the individual outcrop mapped near the town of Fort McMurray in that study. At the tunnel site, measurements of the high-angle planar cross-beds at tunnel elevation correspond well with those reported by Carrigy. The mean dip azimuth at the site is 11°. Also, Carrigy reports a mean dip of 25.13 degrees, close to the 27.78 degrees measured at the tunnel site. Grain size analyses of the cross-bedded sands show them to be of fairly uniform grain size (Figure 3.5, from Carrigy, 1967). Carrigy suggests that the high angle of the dip, the wide variation in dip azimuths of the cross-beds, and the poorly graded nature of the cross-bedded sands in the McMurray Formation could indicate a fluvial environment of deposition in which wide streams of low average velocity meandered across a gently north-sloping floodplain.

The cross-bedded sands within the depth of the tunnel had all of the above attributes and were considered to have been formed under similar conditions. Regionally, this deposit was expected to be continuous in a north-south direction on a scale of ten's of kilometers and in an east-west direction on a scale of, perhaps a kilometer. However, the individual point bars and their associated bed forms were

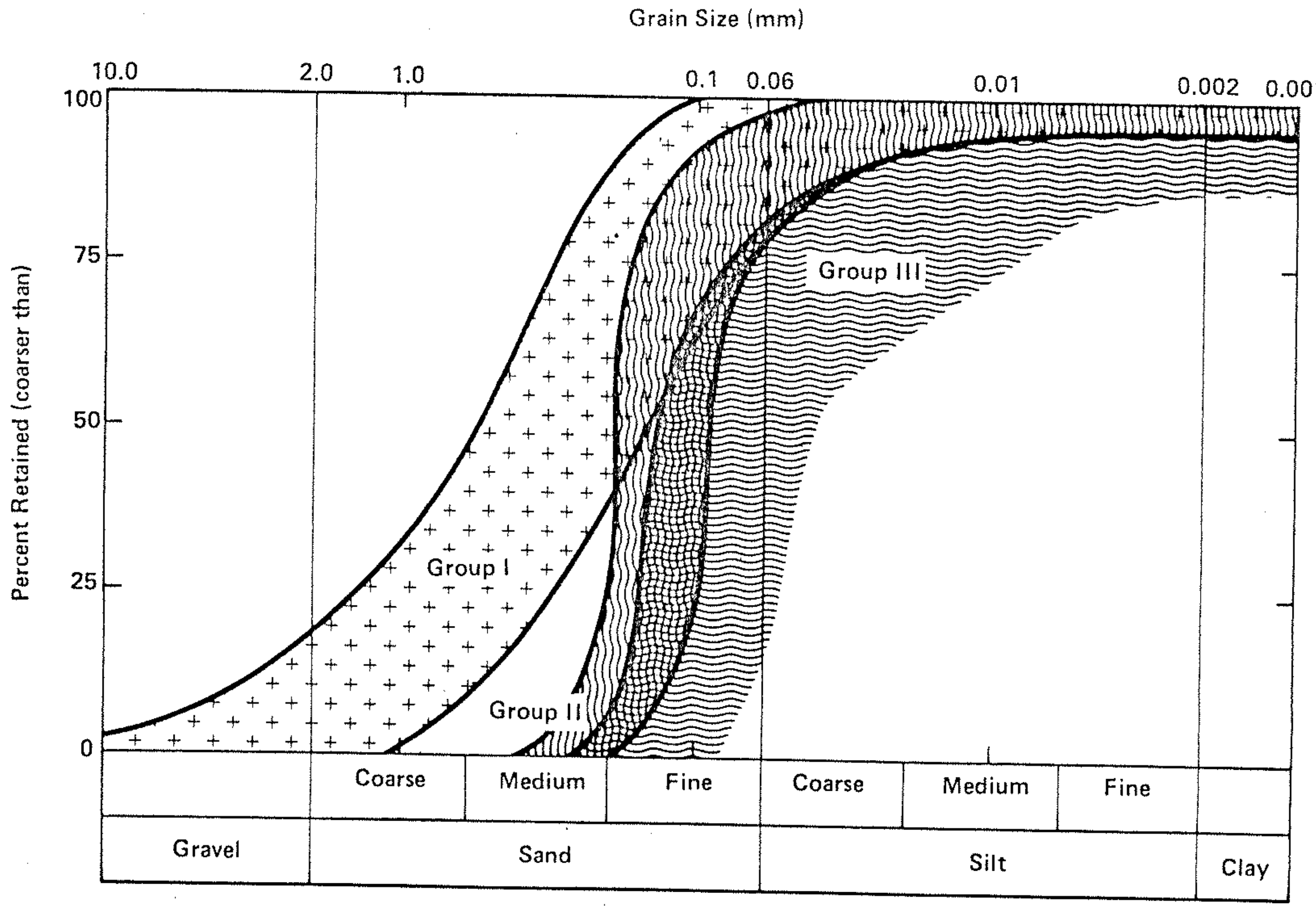


Figure 3.5 GRAIN SIZE GROUPS, ATHABASCA OIL SANDS (from CARRIGY, 1967.)

NOTE: Grain size curves of sands mapped within depth of tunnel excavation, generally fall within Group II.

not likely continuous on more than a scale of a few hundred meters and less. Those observed at the tunnel site and their expected continuity are described below.

The thin siderite-cemented clayey siltstone bed that undulates about elevation 269.1 on the downstream face of the oil sand hill represents a reduction in flow velocity and water depth, during which some of the suspended load settled out. This bed separates the apparently massive rich oil sand from the strongly cross-bedded rich oil sand above (Plate 3.1a). It is suggested that as the point bar forming the top of the massive bed migrated laterally it had a fairly flat top on the landward side of the bank. During flood some water containing only suspended load flowed over the banks and was trapped by small natural levees after the flood waters subsided. The relatively iron-rich silt and clay settled out and was often oxidized in the shallow-water to subaerial environment. This layer protected most of the point bar surface from aeolian re-working (Harms & Fahnestock, 1965). This type of deposit may have been in the order of a hundred meters in lateral extent when deposited. In many cases, as subsequent levels of point bars were deposited as the river continued to meander, these overbank deposits would be eroded by the leading edge of the dissecting channel. Therefore, it is not expected that layers formed in this environment will normally be laterally continuous for great distances. The particular layer at elevation 269.1 at the tunnel site was likely to occur within the excavation within about 1 m of elevation 269.1; however, it would likely be difficult to see when mixed with the rich oil sand and was not expected to create any mining difficulties. Where that layer was expected to occur within a meter of the roof of the excavation, that is, in the downstream 8 m of the excavation, the layer was expected to possibly represent a horizontal plane of easy parting and may have resulted in increased spalling in that part of the tunnel.

Other discontinuous bands of siltstone or ironstone clasts (Plate 3.1b) and occasional wood fragments occur throughout the fluviatile zone. These are normally angular fragments in discontinuous thin horizontal to gently dipping layers. They are thought to have been deposited in continuous layers on the slope of a point bar during a low water period, then broken up by the scouring action of the meander moving the opposite direction, and redeposited in the lower, flatter portion of the scouring channel. They would then be buried by deposition of cross-bedded sand in the point bar accreting from the opposite side of the channel from the scouring edge.

These clasts were expected to occur fairly frequently and irregularly but would likely present no problem for excavation as the individual fragments are generally isolated within a rich oil sand matrix.

Above the elevation of the tunnel excavation, the deltaic foreset beds of middle McMurray (refer again to Table 2.1) are evident. These occur as large scale, low-

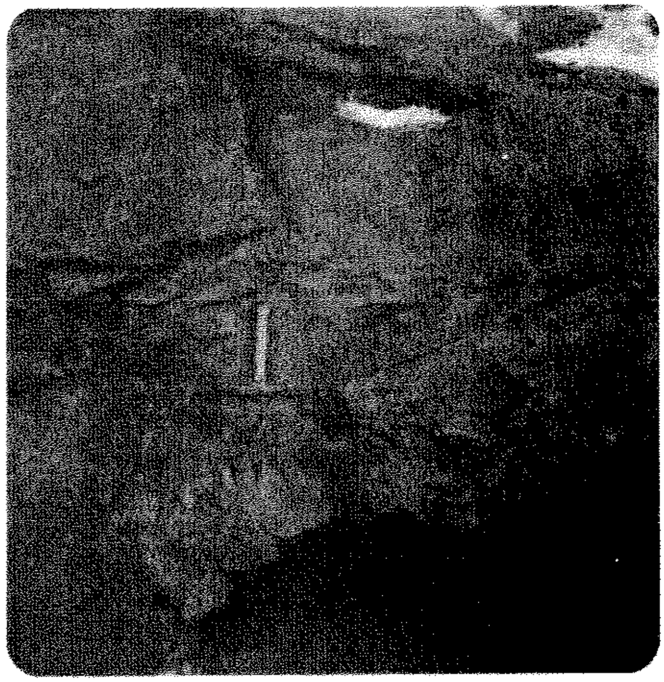


PLATE 3.1a Downstream Outcrop Face.
Hammer head is at elevation 269.1, where thin siderite-cemented siltstone layer separates "massive" rich oil sand below from high-angle cross-bedded rich oil sand above.

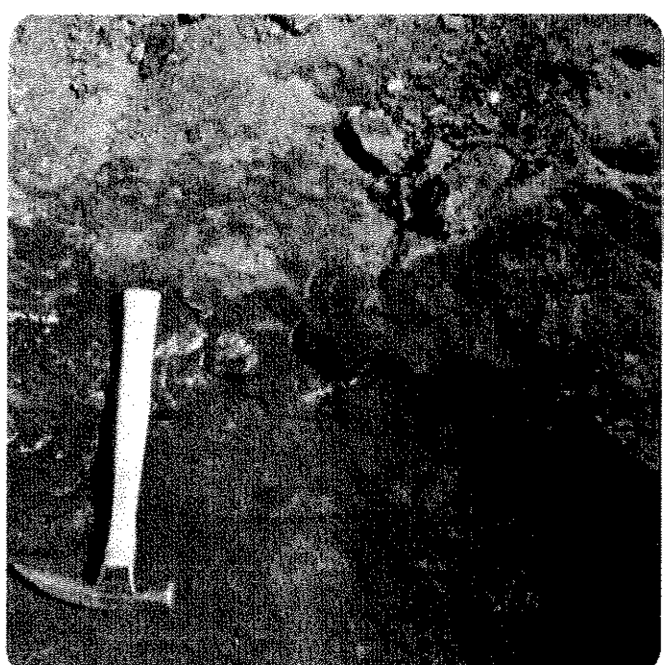


PLATE 3.1b Ironstone Clasts.
The clasts shown are about 3 cm in diameter and occur in a discontinuous, nearly horizontal layer.

angle cross-beds of fine sand separated by thin silt laminae. Abundant burrows were observed in these layers in outcrop and in cores. The observed fining upwards of the overall average grain size is supported by the gradual lessening of the resistivity value upwards and the gradual increase in clay content shown by the gamma-ray value increasing above about elevation 272 m. The deltaic foreset beds were not expected to be encountered within the tunnel excavation.

The gas-rich zones that were identified on the geophysical log of test hole 76-67 at the top and bottom levels of the tunnel excavation would quite likely be encountered in the excavation near the mid-point of the tunnel. Rapid excavation near these zones would possibly result in "thumps", weakening of the oil sand, possible floor heave and then large settlement, and increased roof falls in this area.

3.3 Fracture Phenomena

3.3.1 Structural Mapping Results

Structural mapping of the outcrop faces was carried out in conjunction with the lithology mapping. This section presents the structural observations made; an interpretation with respect to the proposed tunnel excavation is presented in the next section.

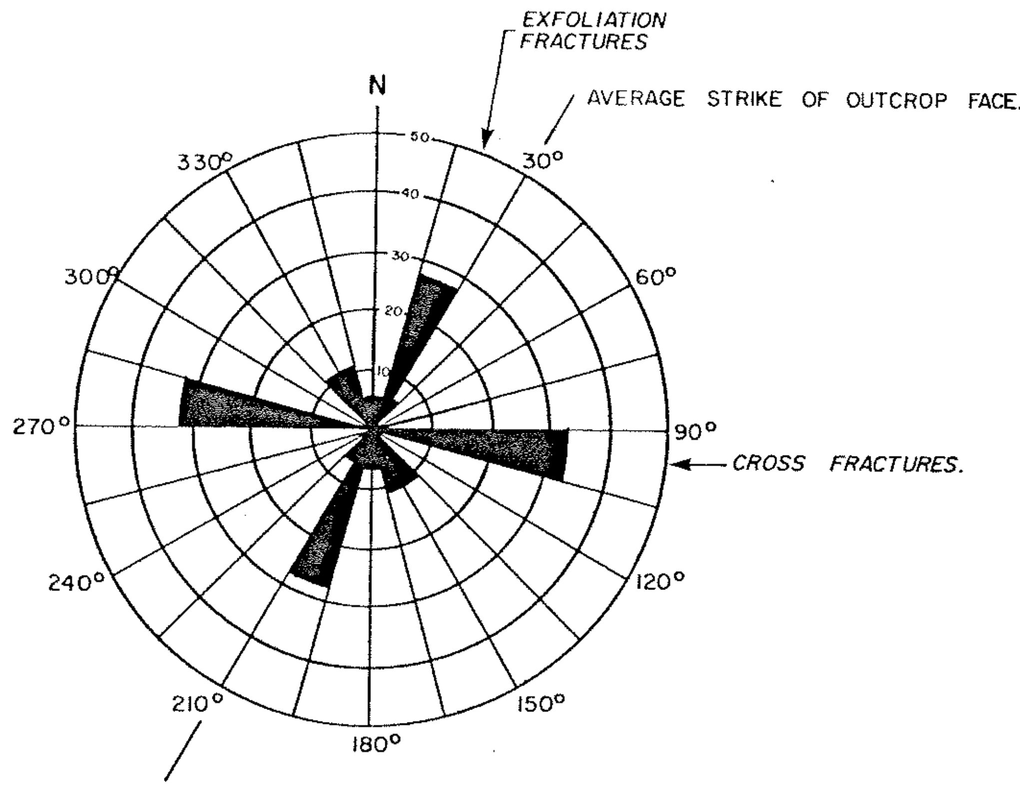
Exfoliation fractures, sub-parallel to each of the two outcrop faces, form the dominant systematic joint set on the rock outcrop through which the tunnel was to be excavated. A second, truncated fracture set occurs on each face at a sub-orthogonal orientation to the dominant set, and therefore is nearly normal to the respective outcrop face. Many of these fractures are curved and thus there is a wide scatter of data about the mean orientation. This second set of fractures is termed cross fractures.

The fracture data collected on the outcrop faces is presented in Figure 3.6 on rose diagrams as percent frequency of total strikes measured. A two-dimensional direction (strike only) analysis is presented as dips of fractures are fairly uniform (near vertical) and this method affords clearer differentiation of dominant fracture sets. No set traverses were made in order that all possible measurements could be taken. Therefore, the relative abundance of fractures of different sets may be unrepresentative but the dominant direction of those sets is discernible. Very few fractures were measured on the upstream outcrop face, but the results are presented for completeness.

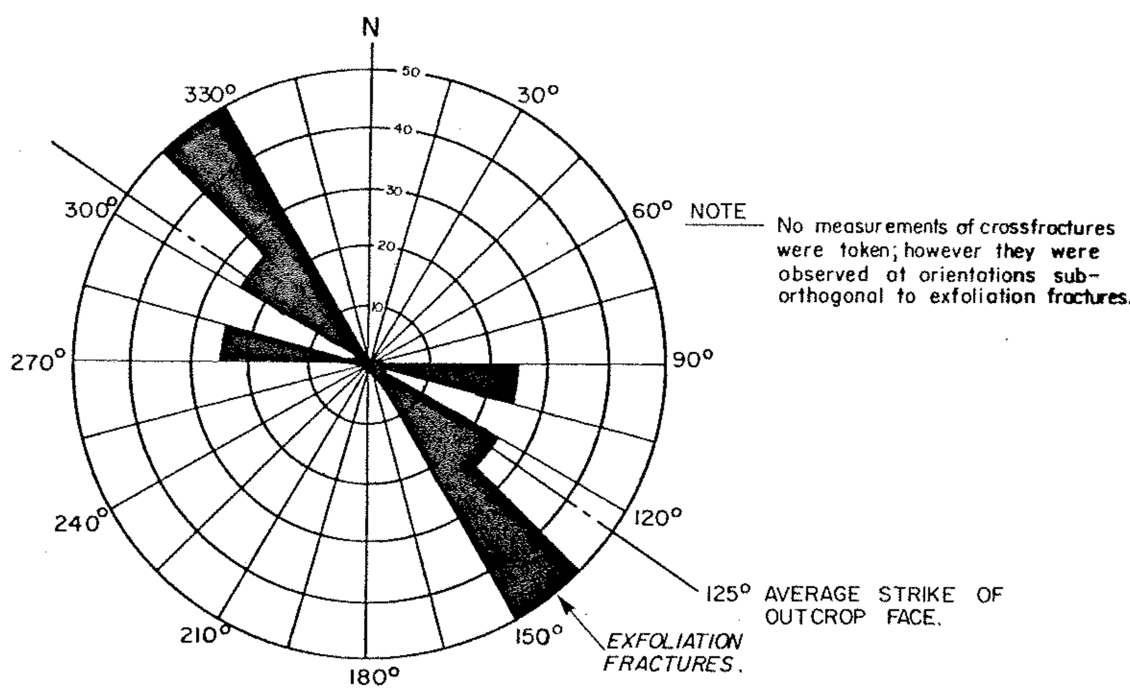
As previously discussed, the cross-bedded oil sand, which was expected to form the roof of the tunnel excavation, fractured in outcrop and in cores along the planes of the cross-beds which had dips ranging from 14° to 37° with a mean dip azimuth of 11°, or almost parallel to the tunnel axis.

3.3.2 Interpretation and Discussion

During mapping of the tunnel excavation, the expected dominant fracture set was the one sub-parallel to the outcrop face nearest to that point in the tunnel. The absolute



a) Downstream Face



b) Upstream Face

Figure 3.6 ROSE DIAGRAMS OF FRACTURES OBSERVED IN OUTCROP

These were measured in the McMurray Formation, on the upstream and downstream outcrop faces at the Saline Creek Tunnel Site. Each concentric circle represents ten percent of the total number of strike azimuths measured.

distance that the exfoliation fractures would penetrate prior to construction was difficult to predict although it was thought that it may be for up to 30 m along the tunnel on the downstream side and slightly less on the upstream side because the angle between tunnel axis and outcrop face strike is greater on the upstream side. The orthogonal truncated fractures were not expected to exist more than a few feet into the tunnel, prior to excavation; however, they were expected to form after excavation due to release of lateral confining pressure on the exfoliation slabs.

The predicted fracture configuration at the tunnel exit portal is presented in Figure 3.7. These dominant fracture orientations were taken directly from the rose diagrams showing dominant outcrop fracture orientations (Figure 3.6). Although very little data was available from the upstream outcrop face, a dominant fracture orientation was predicted for that area also.

It was hoped that an indication of the actual extent and orientation of the fractures would be obtained by mapping the inside of the tunnel as the excavation proceeded. The action of the tunnel excavating machine smearing the fractures and the masking of the fractures by a new set of fractures parallel to the tunnel wall due to stress relief by the excavation, were seen as potential problems. It was expected that, by cleaning the walls and by the appearance of iron staining and other indicators that might become apparent as the work progressed, we would obtain useful information.

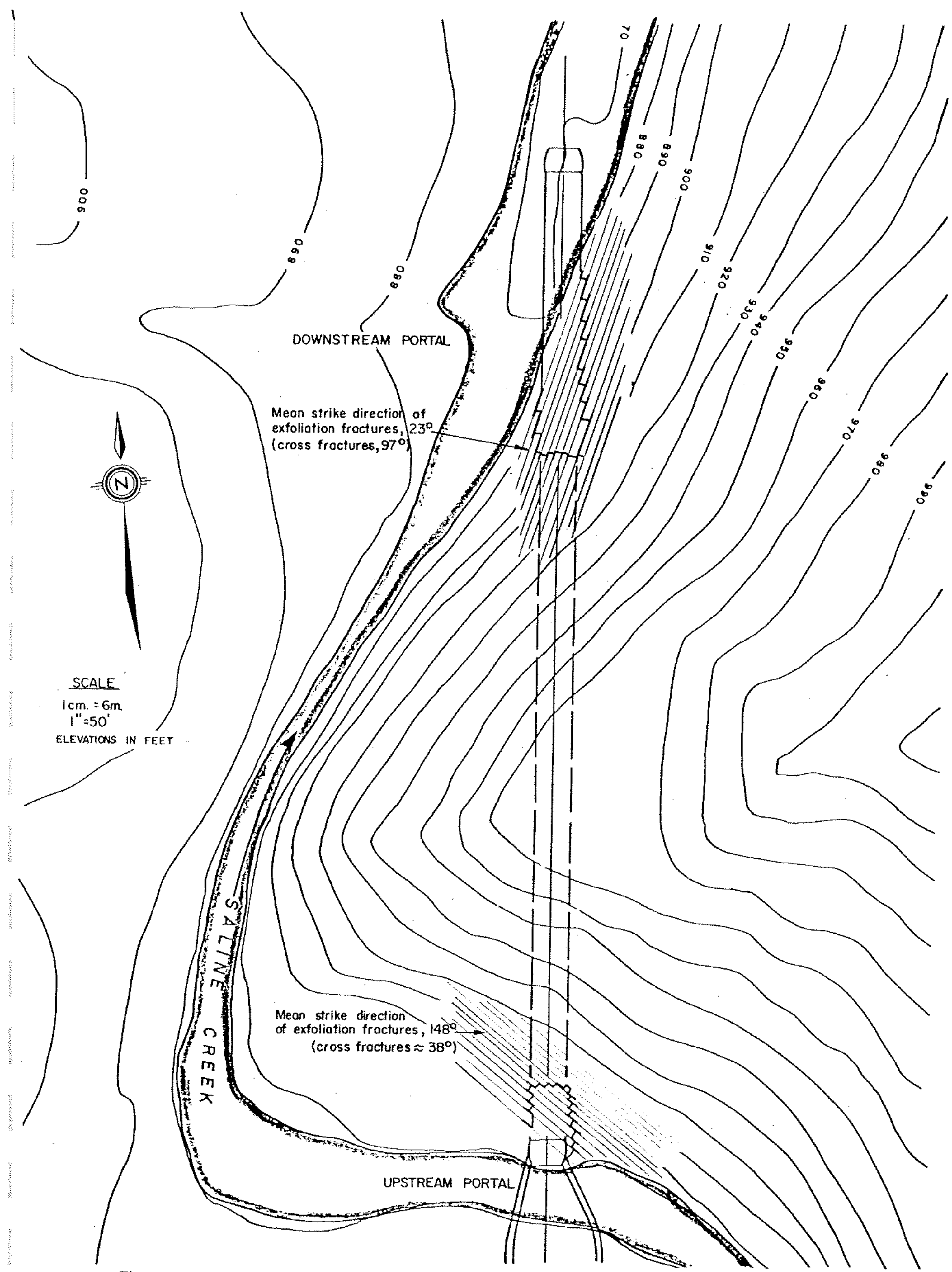


Figure 3.7 PREDICTED FRACTURE CONFIGURATION IN TUNNEL EXCAVATION

It was predicted that fracturing along cross-beds may cause some roof falls in the tunnel excavation, particularly in the central one-third where the magnitude of stress relief was expected to be the greatest. We were, in effect, predicting a stress relief (exfoliation) fracture along a preferential plane of weakness. Since exfoliation fractures occur sub-parallel to the excavation face, the roof falls were expected to occur predominantly where the orientation of cross-beds is sub-parallel to the nearest excavation face.

3.4 Summary of Interpretation

1) It was predicted that the tunnel would be excavated through rich fine- to medium-grained oil sand, deposited in a fluviatile environment by lateral accretion on the inside of meanders of a wide stream.

2) High-angle north-dipping cross-beds were expected to occur throughout the tunnel but to be dominant in the roof.

3) The possibility of a thin ironstone layer occuring near elevation 269.1 was predicted.

4) Discontinuous bands of shale, siltstone and ironstone clasts were expected to occur in the tunnel but to pose no problem to excavation.

5) It was indicated that gas-rich zones may occur near the top and bottom of the tunnel near the mid-point, and that excavation may cause "thumps"

and lowering of the *in situ* strength of the oil sand.

6) It was predicted that a dominant fracture set would appear sub-parallel to the nearest outcrop face (exfoliation fractures).

7) A second set of fractures, termed cross fractures, was predicted to occur orthogonal to the exfoliation fractures.

8) It was suggested that fracturing along cross-beds may produce some roof falls, predominantly where the orientation of the cross-beds is sub-parallel to the nearest excavation face.

CHAPTER IV

GEOLOGIC OBSERVATIONS DURING TUNNEL EXCAVATION

4.1 Introduction

Inspections of the geology at the tunnel site were made periodically during the excavation. As expected, the action of the rotating bit on the oil sand created a smearing of structural features, leaving only relief made mainly by the bit. Furthermore, areas of the tunnel that were excavated between site inspections were somewhat obscured from observation by the steel rings and wire mesh used as temporary support in the tunnel. However, the downstream portal, which was blasted, and the upstream portal, which was excavated with a backhoe, were unobscured and were fairly easily inspected.

4.2 Lithology and Depositional Environment in Tunnel Excavation

Rich oil sand was encountered nearly throughout the tunnel excavation. The sand was fine-grained and well-sorted. In some areas along the length of the tunnel, the top one to two meters appeared slightly less rich and exhibited high-angle planar cross-bedding. The cross-beds were not visible throughout most of the excavation due to the high oil content and the smearing action of the tunneling machine. The lithology as mapped during the excavation of the tunnel, is illustrated in Figure 4.1.

In two small sections, near the exit portal and near the mid-point of the tunnel, the oil sand appeared to fracture along cross-beds for short distances of up to one meter. The fallen blocks were rich oil sand and the fracture faces appeared to be lean to barren oil sand (Plates 4.1a and 4.4a).

Pockets of barren sand were encountered from 1 to 8 m to the east of the tunnel near Chainage 10+00 during drilling of instrumentation holes (Ryzuk, 1977).

Layers of shale and siltstone clasts were encountered at various locations and elevations within the tunnel. These layers were generally discontinuous, typically with several 1- to 2- cm diameter clasts separated by an average distance of about 25 cm. Pyrite balls were occasionally encountered within these layers. These clasts occurred repeatedly at 2 elevations, 266 and 268 m. Also, the beds were continuous at these locations for a length of up to 4 m and a thickness of 2 to 8 cm. The clean upper surface of a shale layer was observed at elevation 264 m near the downstream portal (Chainage 11+40), on the bottom of the tunnel excavation. Thin ironstone layers were observed at elevation 267.9 at the downstream portal excavation and 267.6 and 267.9 near the upstream portal (Chainage 9+10) within the tunnel.

Oil seeps were observed on the side wall of the downstream portal excavation. These occurred along exfoliation

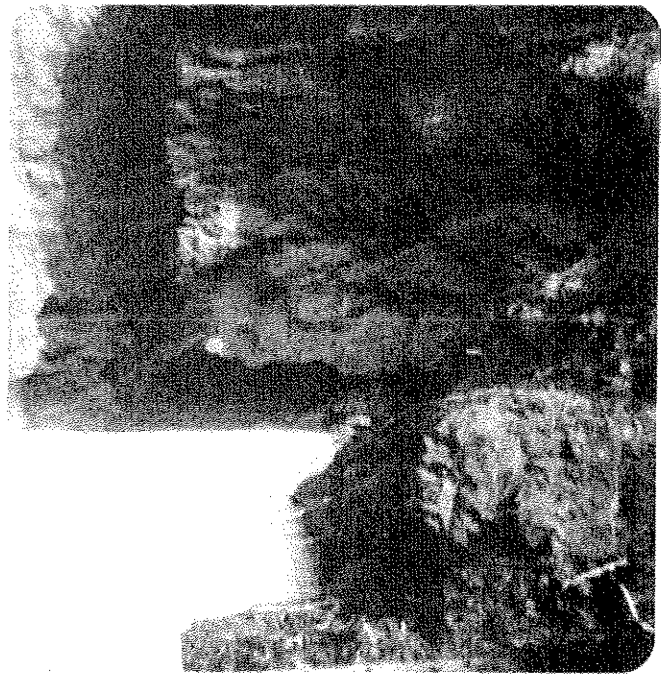


PLATE 4.1a Crown Spalling in Tunnel Exit Portal. Failure planes occur along and across bedding planes of rich cross-bedded oil sand.

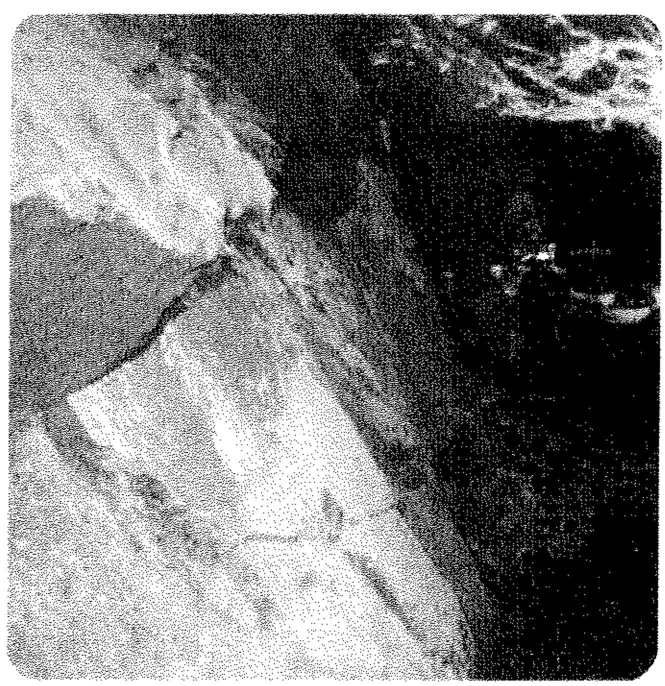


PLATE 4.1b Oil Seep Along Exfoliation Fracture. Exfoliation fracture has slightly undulating face. Irregular orthogonal cross fractures are in foreground.

fractures (Plate 4.1b). One area of oil seepage was observed at the centre of the fresh tunnel excavation face at about the mid-point of the tunnel (Chainage 10+60). The oil appeared to be oozing slowly from rich homogeneous oil sand.

Several small water seeps were observed at a variety of elevations and locations along the tunnel. Two relatively large water seeps were observed at elevation 268.5 at Chainage 10+10, near the mid-point of the tunnel, and at 268.2 near the upstream end (Chainage 9+10).

The seepage appeared to be coming from fine- to medium-grained homogeneous rich oil sand. It appeared that no fractures were related to this seepage. Also, the sand was not noticeably coarser grained than the sand surrounding the seep. Water seeped from these areas slowly, and in some cases the rate of seepage seemed to slow down or stop altogether. Therefore, the seepage may be from small perched water tables that are drained by excavating the tunnel. Chemical analyses indicated a high salt content; however, the relative proportions of anions and cations was not typical of connate water observed at other locations in the McMurray Formation (Hutcheon, 1977). The precise reason for this has not been confirmed.

The depositional environment within the tunnel excavation is considered to have been accurately predicted in Chapter III. As previously discussed, it is likely that most sedimentary features were masked by the tunneling machine smearing the rich oil sand. In particular, high-angle cross-beds were only observed at one location more than a few meters from the outcrop faces that were originally mapped. However, evidence was observed that strongly supports the conclusion of fluviatile, and more specifically, a point bar depositional environment.

Firstly, the oil sand in the tunnel excavation was uniformly rich, fine-grained and well-sorted throughout the height and length of the excavation. High-angle north-dipping cross-beds were observed in the upper 2 meters. This compares well with the lithology that was predicted for the tunnel, which was based on extrapolating observations made in outcrops and test holes.

Secondly, the occurrence of discontinuous bands of ironstone, siltstone and shale clasts corresponds well with the predictions, and supports the conclusion of a fluviatile environment of deposition. The layer that occurred frequently on the outcrop at elevation 269.1 was not observed directly although a prominent band of clasts, continuous in one section, was observed at about elevation 268.2.

These layers appeared to have no direct adverse affect on the actual digging operation due to their small and discontinuous occurrence. However, it is noteworthy that the action of the bit on hard ironstone or siltstone created sparks that would have been a cause of concern where the oil sand emitted flammable gases, had they occurred.

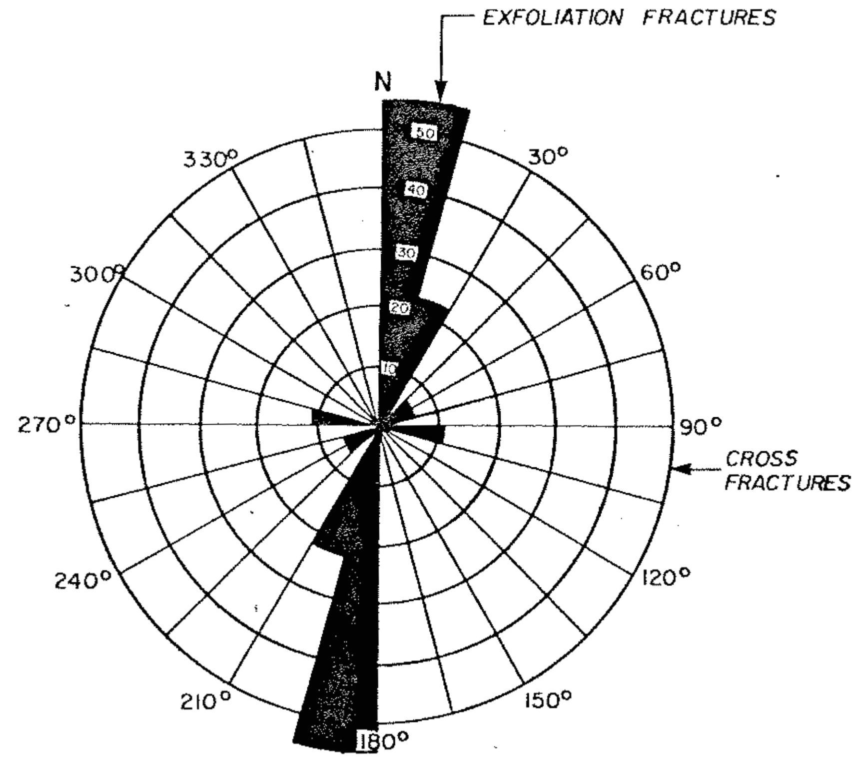
Observations of gas (hydrogen sulfide and methane) release within the tunnel excavation were recorded by others (Srajer and Barron, 1977). Apparently, no abnormally gas-rich zones were noticeable from measurements taken, and no serious "thumps" occurred during excavation. However, some gas must have been released, as indicated by the odor in the air during some stages of excavation. It is possible that the gas-rich zones observed on the geophysical logs and predicted to occur within the tunnel near the top and bottom were localized pockets. This is supported by the fact that the gas-rich zones were not observed at similar elevations and in similar magnitudes in the other test hole (76-76) which was as far from 76-67 as it was from the tunnel excavation.

4.3 Fracture Phenomena In Tunnel Excavation

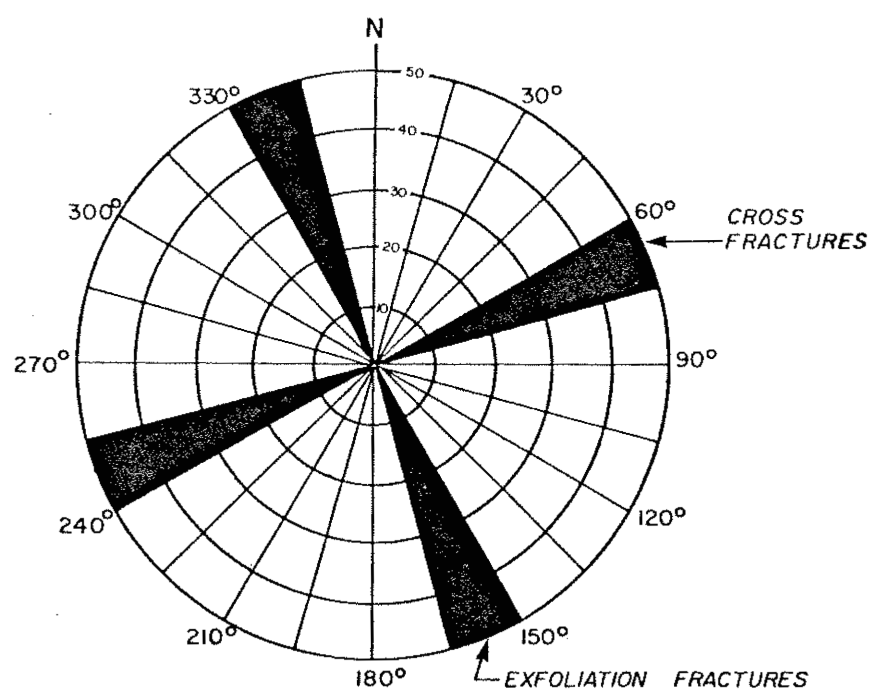
An abundance of exfoliation fractures were observed during the construction of the tunnel, predominantly in the downstream portal excavation. The portal excavation consisted of cutting a right-angled corner into the northern face of the oil sand hill. The east side of the excavation was dominated by exfoliation fractures sub-parallel to the original face of the outcrop. An average spacing of 30 cm between fractures was observed on this face, with no discernible pattern of increasing or decreasing frequency (Plate 4.4b). On the south face of the downstream portal cut, three clean exfoliation fractures were observed at perpendicular distances, of 1.8, 2.7 and 2.8 m from the outcrop face. The furthest that any of the exfoliation fractures were observed from the original outcrop face was 4.9 m, in the southeast corner of the downstream portal cut. Strike measurements from 7 exfoliation fractures in the downstream portal excavation are plotted on a rose diagram in Figure 4.2a. The average dip of the exfoliation fractures was 61°W.

Numerous cross fractures were observed, generally striking in an orthogonal direction to the exfoliation fractures and since they are curved, they dip at a variety of angles. Strike measurements from 2 of these are plotted on Figure 4.2a.

The intersection of exfoliation and cross fractures was observed in a nearly horizontal plane from above the downstream portal, as shown in Plate 4.2a. This compares favourably with the predicted fracture configuration in Figure 3.7. This pattern was only clearly visible where sufficient oil had been weathered from the oil sand that it was brittle enough to break cleanly, that is, in only the outer 1 to 2 m of the outcrop.



a) Downstream portal excavation



b) Upstream portal excavation
(Estimated measurements)

Figure 4.2 ROSE DIAGRAMS OF FRACTURES OBSERVED IN THE SALINE CREEK TUNNEL EXCAVATION, NEAR THE PORTALS

Each concentric circle represents ten percent of the total number of strike azimuths measured. These diagrams are for comparison with Figure 3.6, which shows the fractures measured on the natural outcrops near the above excavations.

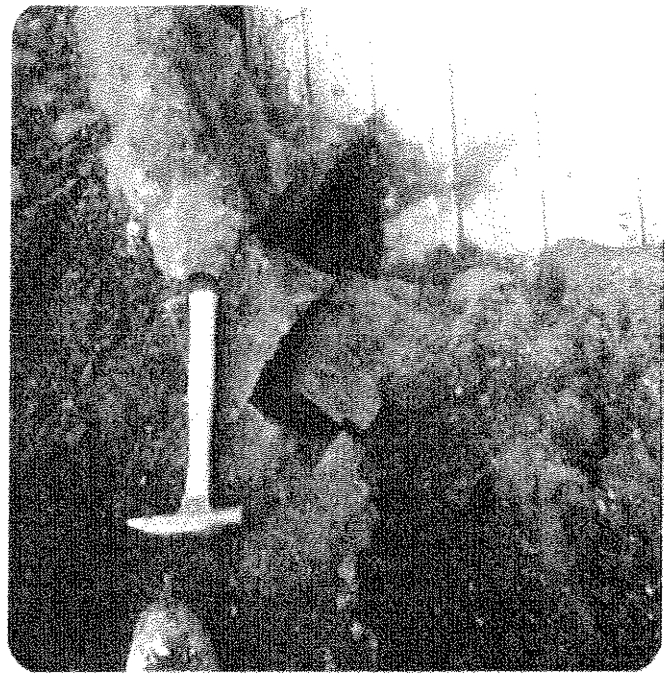


PLATE 4.2a Fracture Pattern in Downstream Portal. Photograph was taken from above crown at tunnel exit. Hammer handle points north, along tunnel axis. Fractures show clearly in weathered oil sand.

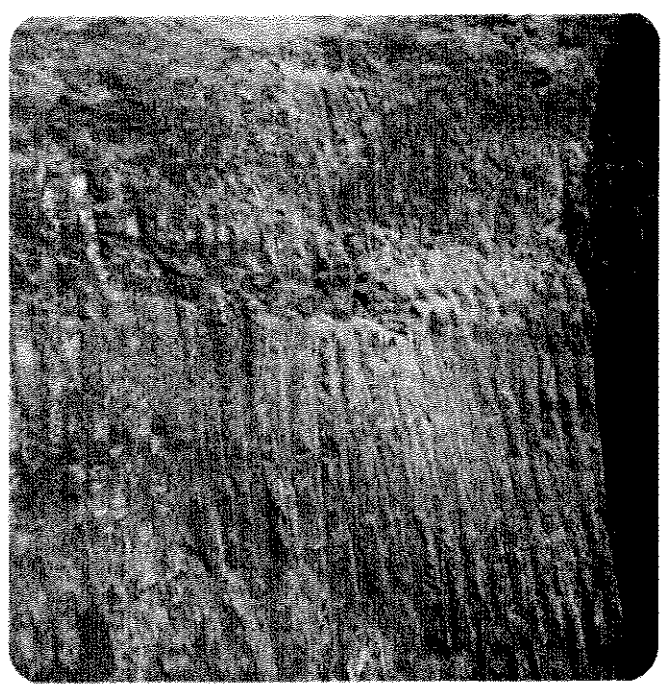


PLATE 4.2b Fracture Pattern in Upstream Portal. Small exfoliation and cross fractures are visible in centre of photo, above a scour surface. Note lenticular nature of sets of high-angle cross-beds.

Most of the exfoliation fractures observed had iron staining or clean fine sand on the surface, indicating that they had existed for some time prior to the excavation. Therefore, blasting likely had little effect on the fractures observed.

In the upstream portal excavation, two exfoliation and two cross fractures were observed (Plate 4.2b). Although measurement was impossible, the estimated strike orientations are 60° for the exfoliations and 150° for the cross fractures. These are shown in Figure 4.2 exfoliation fractures were spaced about 10 cm apart but were only about 20 cm long. They were observed about 1 m in from the original outcrop face, within highly weathered, cross-bedded rich oil sand.

The orientation of exfoliation fractures was predicted with fairly good accuracy, that is, sub-parallel to the outcrop face and steeply dipping. However, the depth to which they might extend was more difficult to predict. At the tunnel site, the maximum penetration observed in 4.9 m perpendicular to the original outcrop face, which is equivalent to a distance of about 12 m along the east wall of the downstream portal excavation. This occurred on the downstream face (northwest facing), where most of the exfoliation fractures were observed. The upstream face (southwest facing) did not exhibit much fracturing on the outcrop, nor within the tunnel excavation. This supports the prediction in Section 3.3, that assumes a greater density of exfoliation fractures on an outcrop indicate that there will likely be a greater number in the excavation at that outcrop.

The cross fractures appear to occur at random orientations, and only as a result of tension caused by exfoliation fractures.

The location of cross-beds was fairly predictable; however, the effect on the tunnel construction was difficult to predict. Cross-beds were prominent in about the upper meter of the downstream portal excavation. They were also observed in the lower elevations of the downstream portal within the so-called massive bed.

Cross-beds were observed throughout the vertical height of the tunnel in the weathered zone at the upstream portal, as seen in Plate 4.2b. They were also observed in the upper few centimeters at some points along the tunnel excavation.

Spalling occurred frequently on the east wall of the downstream portal, around the crown at the downstream end and at the crown in many locations along the tunnel excavation.

The spalled blocks on the east wall of the downstream portal were generally bounded by exfoliation fractures and cross fractures and less frequently by one or more cross-bed planes. The intersection of all three planes on the face, after a block had spalled away, is shown in Plate 4.3a.

The spalled blocks around the crown tended to be bound by exfoliation and cross fractures on the sides and at least partially by cross-bed planes on the top and bottom. There was a visible tendency for the cross-beds to peel off in layers from 1 to 10 cm thick where the orientation of the cross-bed was sub-parallel to the curvature of the tunnel wall (Plate 4.3b). Spalling at this location continued for several weeks and most of it occurred in mid-afternoon when the sunlight was directly hitting that area and the maximum daily temperature was occurring.

Spalling at the crown was difficult to measure quantitatively or to assess the mode of failure, due to the existence of the mesh. However, several blocks of spalled material were obtained through the mesh. Of these, none appeared to have fractured along cross-beds. Each consisted of rich oil sand and had a massive appearance. In one area of the tunnel, fracturing did occur along barren fine sand cross-beds (Plate 4.4a). Again, this occurred where the cross-bed was sub-parallel to the tunnel wall.

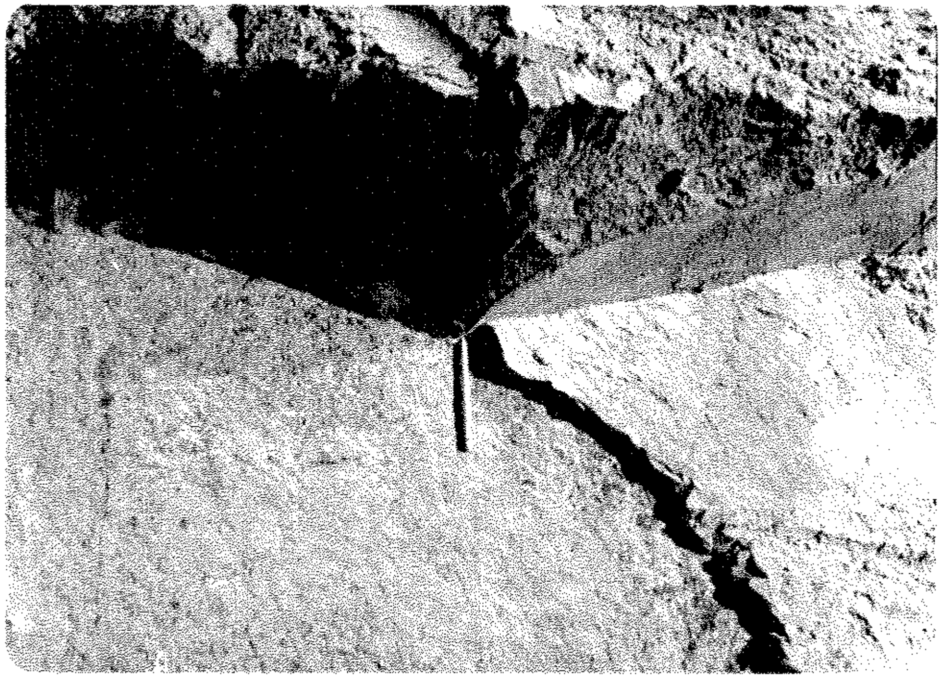


PLATE 4.3a Intersection of Fracture Faces.
Spalled blocks were generally bounded by a combination of the above planes.

PLATE 4.3b Parting Along Cross-beds.
Most of the length of the partings shown above is along cross-beds.

PLATE 4.4a Fracturing Along Cross-beds Inside Tunnel. Fracture face in roof of tunnel, about 35° from crown. Cross-bed plane is sub-parallel to excavated tunnel wall.

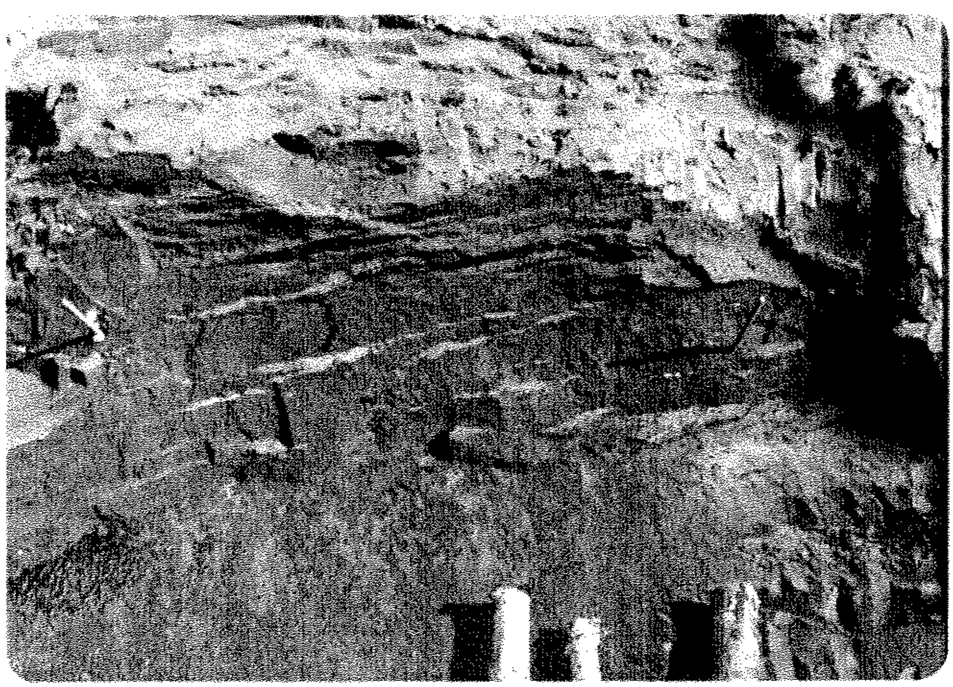


PLATE 4.4b Abundant Exfoliation Fractures. Fractures are sub-parallel to outcrop face. Average spacing here is 30 cm between exfoliation fractures.

A quantitative survey of the crown spalling was made on two occasions, 10 days apart. The spalled material covered an average of about 2 m of the mesh between ribs for the full width. Some sections exhibited no spalling. This type of measurement only is useful to give a relative magnitude of spalling with time. The spalling appeared to extend up to about 1 m above the original excavation line. The spalling in most sections occurred over a period of time but generally most spalling followed excavation by about 10 days. This delay was significant to the mining operation as it was possible to work at the mining face with several meters of unsupported or unprotected roof.

The important conclusion is that spalling partially due to separation along cross-beds did occur under three simultaneous conditions:

1) the cross-bedded oil sand includes thin beds of homogeneous lean to barren sand;

2) the cross-beds were oriented sub-parallel to the face of the excavation, i.e. normal to the direction of stress relief;

3) it is kinematically possible for the block to move.

4.4 Summary and Conclusions

1) Rich fine-grained oil sand, exhibiting both high-angle cross-beds and a massive appearance were encountered within the tunnel excavation. This corresponds well with the predicted lithology which was based on extrapolation of data from outcrop mapping, test hole drilling and geophysical logging.

2) Layers of shale, siltstone and ironstone clasts were encountered at various locations within the tunnel, as predicted.

3) Oil seeps and water seeps occurred at various locations in the tunnel. These were not predicted, but were of insufficient magnitude to adversely affect the tunneling process. It has been hypothesized that the water seeps are from small perched water tables.

4) The tunnel is considered to have been excavated through oil sand deposited in a fluviatile environment, as predicted.

5) Small gas-rich zones were not observed within the tunnel excavation. Interpretation of these and extrapolation from the geophysical holes to the tunnel excavation cannot be carried out with great confidence.

6) Exfoliation fractures, sub-parallel to the outcrop face, were abundant near the downstream face (northwest facing). They were much less abundant on the flatter, upstream face (southwest facing). The orientation of these fractures was predicted with fairly good accuracy.

7) Spacing of exfoliation fractures averaged 30 cm with a minimum of about 2.5 cm observed. No pattern of increasing or decreasing frequency was discernible.

8) The furthest that any of the exfoliation fractures were observed from the original outcrop face was 4.9 m.

9) Cross fractures were observed striking in an orthogonal direction to the exfoliation fractures.

10) Spalling occurred frequently on the east wall of the downstream portal, around the crown at the downstream end and at the crown in many locations along the tunnel excavation. The blocks were generally bounded by exfoliation and cross fractures and occasionally by cross-beds, particularly where the cross-beds were oriented sub-parallel to the face of an

excavation. This phenomenon was predicted in Chapter III.

11) The crown spalling generally followed the excavation by about 10 days.

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