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The MacKay River Terrain Analysis and Landslide Inventory

By

Douglas L. Dewar

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

Department of Civil Engineering

Edmonton, Alberta

Fall 1996

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for the acceptance, a thesis entitled The MacKay River Terrain Analysis and Landslide Inventory submitted by Douglas L. Dewar in partial fulfillment of the requirements for the degree of Master of Science.

Dr. D.M. Cruden (Supervisor)

Dr. D. Chan

Dr. R.B. Rains

Abstract

The MacKay River flows through Syncrude Canada Limited Leases 17 and 22 which are located 30 km north of Fort McMurray in northeastern Alberta. The river is actively downcutting and meandering. An air photograph interpretation and landslide inventory were completed in April 1995, covering the lower 75 kilometres of the river valley. A meander cut-off occurred between 1953 and 1958 in the study area. There are 140 landslides in the river valley with crests larger than 40m and volumes of up to $1.4 \times 10^5 m^3$.

Modes of movement found in field investigations include: debris slides and flows, rotational and translational earth slides, earth flows and rock falls, topples and slides. Movements with surfaces of rupture deeper than 5m are in the Clearwater Formation clay-shales. Shallow movements with surfaces of rupture at less that 5m depth occur in the colluvium, river terrace deposits, glacial sediments and McMurray Formation oil sands.

Acknowledgements

The author would like to thank Dr. D.M. Cruden, Professor of Civil Engineering at the University of Alberta, for giving guidance and advice during the preparation of this thesis. Special thanks goes to Dr. B. Rains, Associate Professor of Earth and Atmospheric Sciences, for advice on the geomorphological aspects of this thesis. I would like to thank Ted Lord, Graham Cuddy and Gord Mckenna of Syncrude Canada Limited for supporting the work through the Industrial NSERC program. Accommodations and field support during the field season were graciously provided by Chris Grapel.

I would like to note the contributions of the following people to this thesis. The names are not listed in any order of importance.

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- Gerry Cyre, Steve Gamble and Christine Hereygers of the Civil Engineering Department for providing field gear,
- Tom Coolen, Doug Karmen, Steve Gaudet, Heather Ferguson, Lynne Thurman and Bruce McMullin of Syncrude Geology for the help and advice and access to the Syncrude borehole database,
- Peter Ormond, Philip Lobo and Chris Grapel for assisting me during field investigations and
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Table of Contents

List of Figures

Page

Page

List of Tables

Chapter 1 Introduction

Syncrude Canada Limited operates one of the largest open pit mines in the world. The mine site is located 30km north of Fort McMurray, Alberta and has been producing synthetic crude oil since 1979. Figure 1.1 is a map of Alberta showing the location of Leases 17 and 22 and the surrounding area.

The understanding of geomorphological processes that will affect the lease-closure landscape is critical to designing long-term lease closure plans. One of these processes is landsliding. The MacKay River flows through Syncrude Leases 17 and 22 and is actively downcutting and meandering. There are landslides throughout the river valley. Rains (1994) and Rains and McKenna (1995) recommended a terrain analysis and an investigation and characterization of the landslides along the MacKay River as a high priority because of the proximity of the river to planned abandonment tailings structures. This thesis work was commissioned based on that recommendation and is sponsored by Syncrude Canada Limited and the Natural Science and Engineering Research Council Industrial Scholarship program.

The information in this thesis will aid in the understanding of landsliding along the MacKay River to better predict the geomorphic processes and the long-term changes in position of the river valley rim and provide reconnaissance-level data for future designs in the river valley. The thesis will also document the active erosion in the valley. An understanding of the mechanisms that cause landslides can improve future mine-slope and foundation designs in similar geological units elsewhere on the Syncrude leases.

The work began with a literature review and air photograph interpretation starting in April, 1995. The primary goal of the air photograph interpretation was to select landslide sites along the MacKay River for field investigations. Six sites were selected on the basis of the information obtained during an aerial reconnaissance of the river valley on May 8, 1995. The literature review and air photograph interpretation are discussed in Chapters 2 and 3.

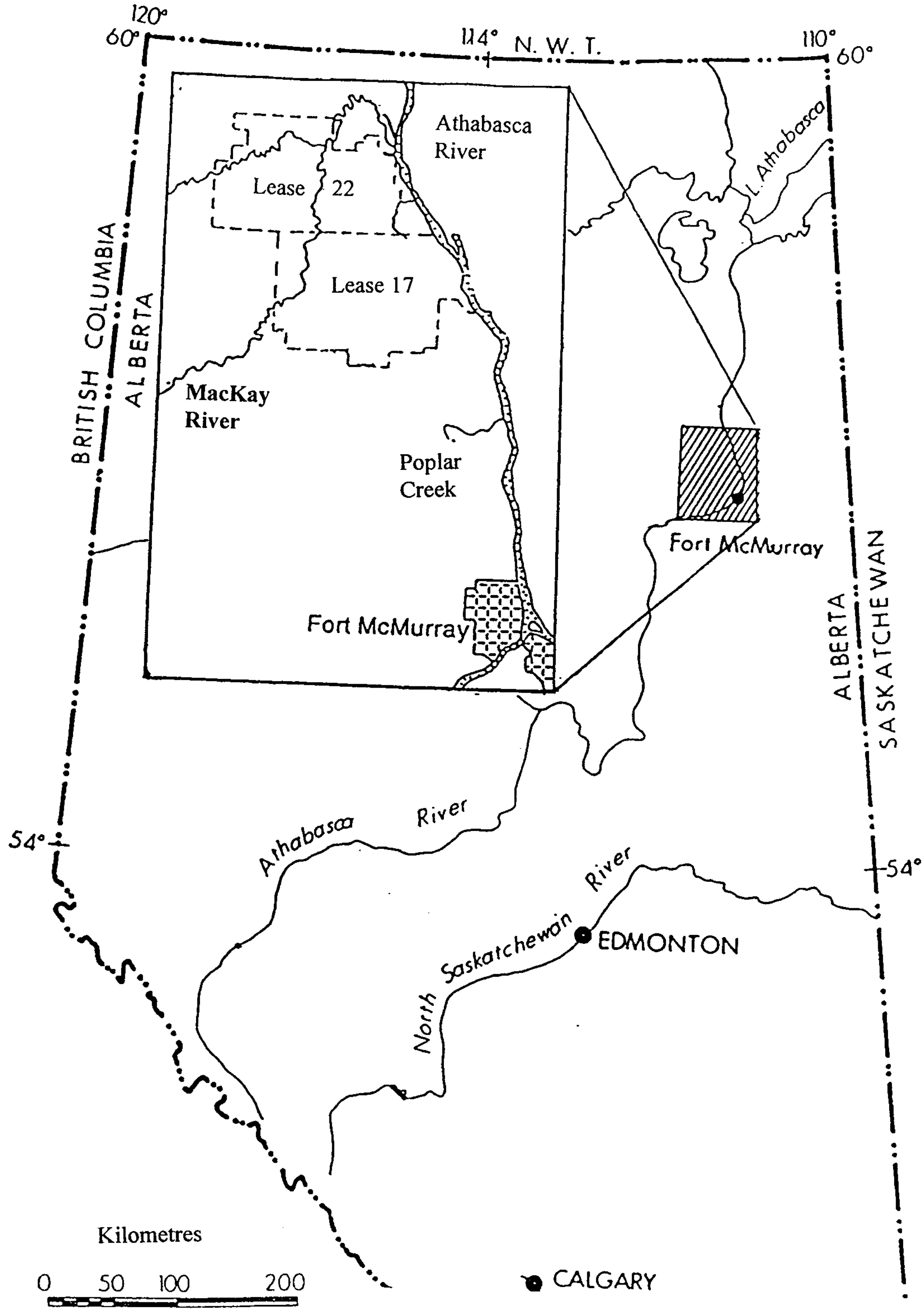


Figure 1.1. Location of Syncrude Canada Limited Leases 17 and 22 and MacKay River.

The next stage of research involved field investigations of the six representative landslides during the summer of 1995. Field work involved ground proofing the air photograph interpretation, measuring slide profiles, mapping the slide lithologies and collecting soil and rock samples. Samples were sent to the geotechnical soils laboratory at Syncrude for testing. The six landslides are discussed in Chapters 4 to 7.

The third stage of the project involved a helicopter reconnaissance of the river valley on August 31, 1995 and a canoe trip on September 18 to 21, 1995 to check the air photograph interpretation. Observations during these investigations are included in the air photograph interpretation (Chapter 3) and in the discussions of the landslides visited during field investigations (Chapters 4 to 7).

Syncrude has a database of index and advanced geotechnical tests for the soil units on its leases, therefore no additional geotechnical testing was performed at the University of Alberta. A review of Syncrude files and reports provided the geotechnical properties of the soil units found in the MacKay River valley.

Slope-stability analyses are performed to model the translational earth slides (Chapter 4) along sections of the MacKay River which contain sheared clay layers and the retrogressive rotational earth-slide earth-flows (Chapter 6).

Chapter 8 is a discussion of the results of the field investigations and the air photograph interpretation. Conclusions and recommendations for further research are included in Chapter 9.

The terminology used to describe landslides in this thesis is from Cruden and Varnes (1996). Dearman et al. (1972) is the reference for the format of geological figures.

Chapter 2 Literature review

2.1 Middle to Late Pleistocene glacial history

Klassen (1989) noted that there was much debate over the timing of many of the glacial events between 790 and 50 ka BP (thousands of years before present, Middle Pleistocene to the middle Wisconsinan of the Late Pleistocene) because of the lack of related glacial deposits in southern Alberta and the range of radiocarbon dating was beyond the age of these periods. Klassen (1989) and Fulton (1989) stated that there were multiple glaciations in southern Alberta. Conversely, Young et al. (1994, p.686) concluded that "most of southern and western Alberta did not undergo Laurentide glaciation prior to the last advance." The conclusion was based on the absence of Canadian Shield clasts in preglacial valley fills (Saskatchewan gravels and sands) in the Edmonton area and on till-facies stratigraphy (Young et al. 1994). There were no multiple till sequences found during field investigations for this study or recorded in Syncrude borehole logs, therefore I believe that the study area has undergone only one glaciation probably in the late Wisconsinan.

The late Wisconsinan Laurentide ice sheet reached its maximum southwestern extent and volume approximately 18 000 years ago (Klassen 1989). The area drained by the present MacKay River was covered by a minimum of 2km of ice at that time (Rains 1994, Fig.2). Rains and McKenna (1995) stated that there were likely two major erosional events that removed most of the pre-existing Quaternary sediments in the area around Syncrude Leases 17 and 22. A hypothesized Livingstone Lake subglacial sheet-flow flood possibly occurred between 18 and 15 ka BP, although the actual event is believed to have lasted for approximately 3 weeks (Rains et al. 1993). It is believed that water flowed southwestward below the ice sheet from northern Saskatchewan, across much of Alberta. The flood became more channelized as the discharge decreased (Rains et al. 1993). It was estimated that the total volume of water discharged by the flood was 84000 km^3 at a rate of $1x10^6$ m^3/s at maximum velocities of 5m/s (Rains et al. 1993).

The subglacial megaflood is believed to have stripped most of the Pleistocene glacial deposits from the area.

After 18 ka BP, the margins of the ice sheet retreated as the climate warmed. Syncrude Leases 17 and 22 emerged from under the ice between about 11.5 and 10.5 ka BP (Dyke and Prest 1987) and were covered by Glacial Lake McConnell. The area emerged from under water as retrogressive offlap ensued.

A second major erosional event was the Glacial Lake Agassiz northwestern, open-channel flood that stripped much of the remaining Quaternary sediments from Leases 17 and 22 and elsewhere. Smith and Fisher (1993) believed that an ice dam impounding the Glacial Lake Agassiz was breached causing a flood that flowed west down the Clearwater River valley, then turned north down the Athabasca River valley. The flood had an estimated mean velocity of 13m/s and a discharge of about $2.4 \times 10^6 m^3/s$ for a duration of approximately 78 days (Smith and Fisher 1993). The Mildred Lake and Ruth Lake depressions on Lease 17 and the fluvial deposits in the area were probably results of the paleoflood. Smith and Fisher (1993) also believed that the majority of the material eroded by the Glacial Lake Agassiz paleoflood was deposited in the Athabasca River delta 100 km north of the Syncrude mine site. This theory also explained the oversized Clearwater River valley and Athabasca River valley (north of Fort McMurray). There are no glacial deposits or only a veneer (1m) of glacial deposits in the area surrounding the rim of the MacKay River valley near the mouth of the MacKay River (*refer to* Figure 2.2b).

Rains and McKenna (1995) stressed that the initiation of all river and creek reaches in the study area could be dated at about 9.9 ka BP, after the Glacial Lake Agassiz paleoflood occurred. Radiocarbon dates on which that interpretation was based were from Smith and Fisher (1993).

2.2 Geology of the MacKay River valley

The bedrock formations and surficial deposits in the MacKay River valley are summarized in this section. Formations and surficial deposits are ordered sequentially from oldest to youngest. Figure 2.2a shows the stratigraphic sequence for the area and Figure 2.2b shows the bedrock contacts at river level on a map of the study area. Figures similar to Figure 2.2b are used throughout this report to show the locations of various features in the MacKay River valley. Locations on the MacKay River are referred to by their distance from the confluence with the Athabasca River measured along the thalweg of the valley (i.e. km 9 is 9 km from the mouth of the MacKay River).

2.2.1 Devonian Waterways Formation

The Waterways Formation consists of gently-folded, alternating successions of rubbly, thinly-interbedded, argillaceous limestones and shales interbedded with massive, jointed limestones (Babcock 1975). The outcrops on the MacKay River are of the Upper Moberly Member of the formation. In some areas, a layer of medium-plastic residual soil, that is part of the Waterways Formation and is up to 3m thick, marks the McMurray-Waterways contact. Syncrude refers to this deposit by the genetic term paleosol (Lobb and McMullin 1989).

The Waterways-McMurray river-level contact is shown in Figure 2.2b. The MacKay River is incised into the Waterways Formation from km 0 to 23 (Figure 2.2b).

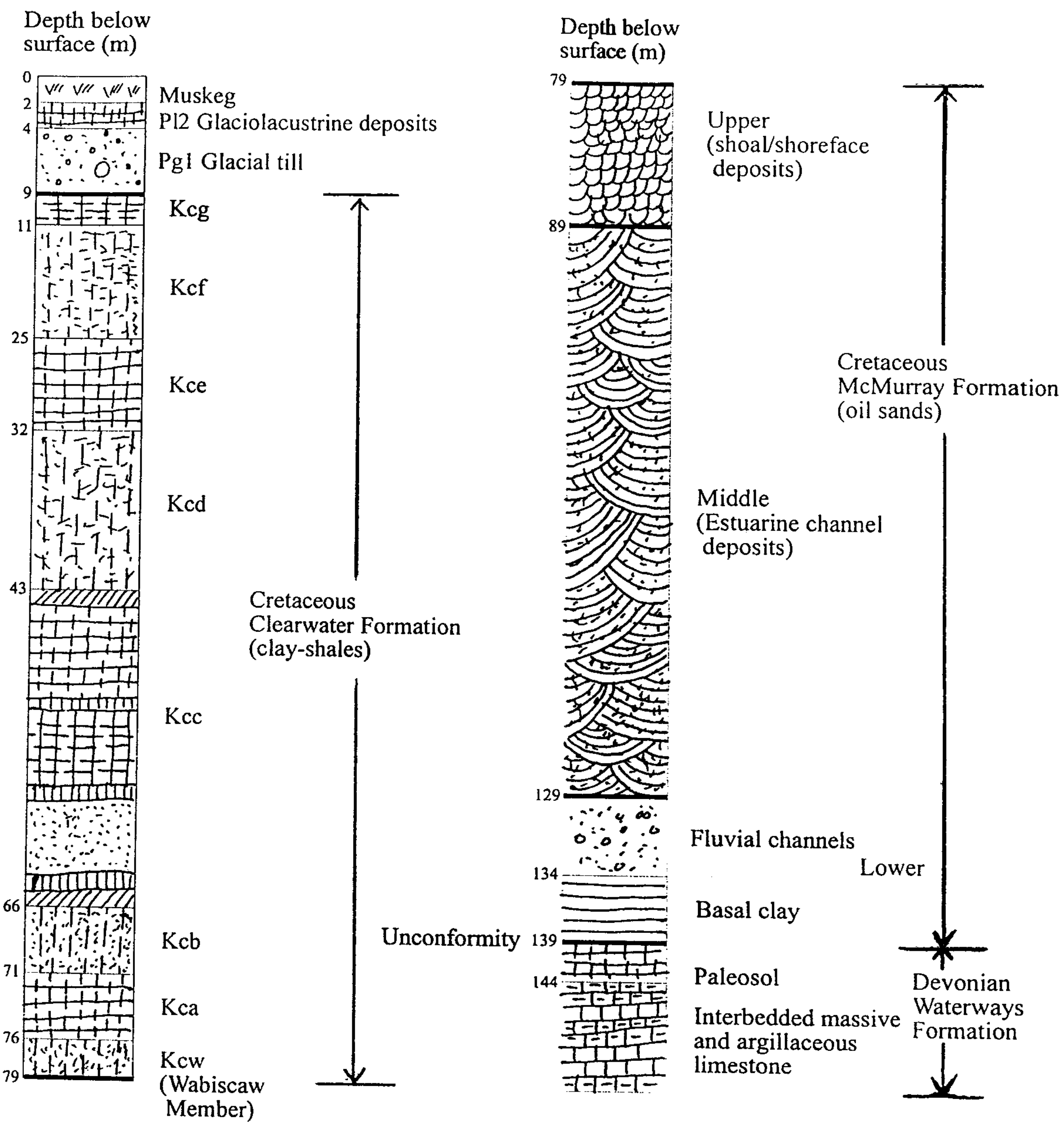
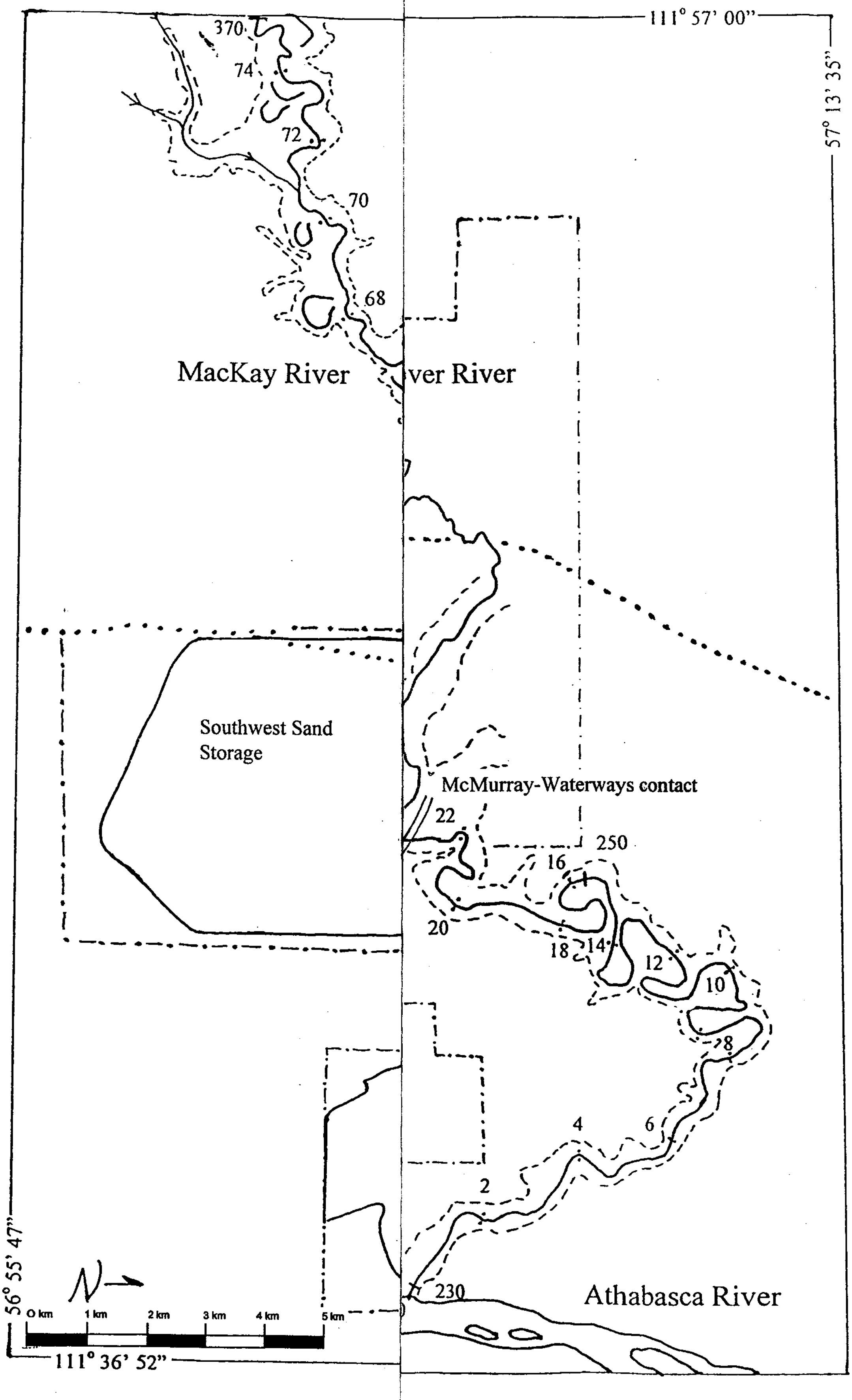


Figure 2.2a. The statigraphic sequence in the southwestern corner of the study area (Carrigy 1966, Lobb and McMullin 1989 and Kosar 1992). Soil symbols are from Dearman et al. (1972).


111° 57' 00"
57° 13' 35"
370
74
72
70
68
MacKay River
ver River
Southwest Sand
Storage
McMurray-Waterways contact
22
250
16
20
18
14
12
10
8
6
4
2
230
Athabasca River
N
0 km
1 km
2 km
3 km
4 km
5 km
56° 55' 47"
111° 36' 52"

2.2.2 Cretaceous McMurray Formation

The McMurray Formation unconformably overlies the Waterways Formation and is informally divided into 3 members: lower, middle and upper (Carrigy 1966). Mattison (1987) developed a generalized stratigraphic sequence for the McMurray Formation based on sedimentologic, ichnologic and paleontologic criteria in the Athabasca Oil Sands area.

The lower member is a sequence of coarse grained sands exhibiting cross-stratification overlain by silts and shales deposited on floodplains. The lower member is a fluvial deposit that is only developed locally in the deepest depressions in the underlying Devonian Waterways Formation (Mossop and Flach 1983). This member can be found in outcrops along the MacKay River from km 4 to 8. Occasionally overbank and pond muds are present in the lower member below the coarse sand deposits. Syncude refers to these deposits as basal clays (Lobb and McMullin 1989). The basal clays are sheared and have low residual shear strength ($\varnothing'_r$) values, but contain no smectitic swelling minerals (Dusseault 1977).

The middle member is a sequence of estuarine channel sand deposits overlain by shale and interbedded sand. This member is generally highly impregnated with bitumen. Cross-beds at the base of the member are characteristically steep (10 to 35 degrees) and are less steep higher in the sequence (8 to 12 degrees) (Mossop and Flach 1983). The mineralogy of the middle member is extremely mature and stable with 95 percent quartz grains, 2 to 3 percent feldspar grains and 2 to 3 percent mica flakes, clay minerals and trace minerals (Mossop 1980).

The upper member is shoal/shoreface sands that are relatively flat- lying and fine grained (Mattison 1987) with small, reverse cross-beds caused by tidal action (Dusseault 1977). The upper member is overlain by shaley and glauconitic sands of the Wabiscaw Member (Kcw) of the Clearwater Formation deposited in a continental shelf environment.

The McMurray-Clearwater and McMurray-Waterways contacts are shown on Figure 2.1b. The river is incised into the McMurray Formation from km 23 to 42 (refer to Figure 2.1b).

2.2.3 Cretaceous Clearwater Formation

"The Clearwater Formation forms the reservoir cap for the oil sands and consists primarily of laterally extensive, flat lying clay-shale, clay silts and fine grained sands deposited in a shallow marine environment" (Kosar 1992, p.29) and conformably overlies the McMurray Formation.

The Clearwater Formation has not been divided into formal members (Isaac and Dusseault 1984), except for the Wabiscaw Member (Kcw) that overlies the McMurray Formation. The formation has been divided into seven informal members by Syncrude geologists based on characteristic geophysical log responses (Isaac and Dusseault 1984): Kca, Kcb, Kcc, Kcd, Kce, Kcf and Kcg. These members are listed from oldest to youngest. All members vary laterally in thickness and lithology. The Kca, Kcc and Kce tend to be clayey and the Kcb and Kcd tend to be sandy. Members tend to alternate in glauconite content with the Kcw, Kcb, Kcd and Kcf members being rich in the greenish mica group mineral. The material is very heavily overconsolidated because it was buried under 1000 metres of overburden before regional uplift and erosion (Lobb and McMullin 1989). During burial the sediments were subjected to temperatures of up to 40°C (Kosar 1992). The regional dip of the Clearwater Formation is approximately 0.1 to 0.4 degrees towards the southwest (Klohn Leonoff 1990).

Many of the bentonitic clay layers in the formation are sheared and are at their residual strength. Morgenstern (1989) suggests some processes that would cause the shearing of these clay layers:

1) Bedding plane slip associated with anticlinal rebound in response to valley formation,

2) Tectonic and

3) Shearing associated with glacial tectonics.

Eigenbrod and Morgenstern (1972) speculated that another possible mechanism to shear clay layers is the swelling of clay layers between non-swelling layers. Swelling is probably not a factor in the shearing of clay layers because of the low permeability of the surrounding clay-shales in the Clearwater Formation. However, there were aquifers of sandy Clearwater Formation layers found during field investigations in the formation.

Matheson and Thomson (1973) compared the rebound of a river valley to that of an excavation, with the difference being the time scale. Elastic rebound of the bedrock below the valley floor and the inward movement of the valley walls are caused by vertical and lateral stress relief. The high lateral stresses in the Clearwater Formation cause relatively large horizontal movements in the valley walls. Kosar (1992) stated that the orientation of the maximum principal stress in the oil sands is horizontal and K_o (the ratio of horizontal and vertical in-situ stresses) is between 1.3 and 2.0. The state of stress in the overlying Clearwater Formation bedrock is probably similar. Gronseth et al. (1989, p.198) noted that "the variability of in-situ stresses has been demonstrated in the Clearwater Formation near Cold Lake, Alberta which have shown that horizontal stresses can be less than, equal to or greater than the vertical stress within an area of several square kilometres". Valley rebound is characterized by an upwarping of the beds in the valley wall and a raised river valley rim in flat lying areas (Matheson and Thomson. 1973). The upwarping of the of the beds in the valley wall cause displacements in weak clay layers that can reduce their shear strength to residual values. I predict the magnitude of valley rebound as no greater than 1 percent of the depth of excavation of the MacKay River valley (30 to 40cm) using Figure 11 of Matheson and Thomson (1973, p.961). In field visits, no evidence of a raised river valley rim along the MacKay River was found, although heavy overgrowth and landsliding in the surface deposits may hide such features. The absence of a raised river valley rim can be attributed to the relative size of the valley and the thickness of the Clearwater Formation. The magnitude of rebound increases with increasing valley depth and increasing clay-shale thickness under the valley. Typical valley depths in the study by Matheson and Thomson (1973) were 200m and the thickness of the clay-shale formations were over 1000m as compared to a valley depth of 40m for the lower MacKay River and the Clearwater Formation thickness of approximately 60m. Therefore, it is probable that valley rebound is not the cause of the sheared bentonitic clay seams.

Issac and Dusseault (1984, p.105) stated that "there has been no tectonism or faulting of any consequence" since maximum burial "except for karst solution collapse within the Devonian limestones and glacial thrusting". It is probable that the shearing of clay layers is not caused by karst collapse because Hackbarth and Nastasa (1979, Fig.12) show no depressions in the limestone in the study area. Therefore, the most probable cause for the sheared clay layers is glacial tectonics. The bedrock was sheared by the advancing ice sheets that were over 2000m thick. Tsui et al. (1987, p.1) stated that "ice-thrust features are known to be widespread on the Prairies in North America".

The Clearwater-McMurray river-level contact is shown in Figure 2.2b. The MacKay River is incised into the Clearwater Formation from km 42 to the south end of the study area (refer to Figure 2.2b).

2.2.4 Pleistocene and Holocene deposits

The study area is covered by a blanket of glacial sediments up to 20m thick (typically 10m), though glacial sediments in the lower 10km of the MacKay River valley were possibly washed away by the Glacial Lake Agassiz paleoflood. The surficial deposits in this area are Holocene aeolian sands and silts which are up to approximately 6m thick.

The glacial blanket of material in the study area usually consists of:

1. A 2 to 5m thick layer of Pl_2 (Lobb and McMullin. 1989), glacio-lacustrine silts and clays deposited in Glacial Lake McConnell and

2. A 5 to 15m thick layer of Pg_1 (Lobb et al. 1989), till.

Buried channels of glacio-fluvial deposits are occasionally found outcropping in the river valley. These channels are disscussed in Section 3.2 and shown on Figure 3.1.1. Lobb and McMullin (1989) also showed that Pf_4, glacio-fluvial outwash sands, can be found in a few locations near the river valley above the till. The blanket of glacial material is overlain by a blanket of muskeg and highly organic soil up to 6m thick behind the river valley rim. The Pleistocene and Holocene deposits are discussed in detail by Lobb and McMullin (1989).

The youngest deposits in the river valley are the colluvium (H_e) which covers most of the river valley and the river bed and terrace deposits (H_f, *refer to* Section 3.3).

2.3 Previous work on MacKay River

2.3.1 Fluvial geomorphology reconnaissance

This section is a summary of the report by Rains (1994) for Syncrude on the geomorphology of the MacKay River valley. That report was summarized by Rains and McKenna (1995), who stated that the Athabasca River was a stable base for the local tributaries because:

1. The relatively straight reach of river bordering Leases 17 and 22 was not likely to alter course over the next few thousand years and

2. The low gradient of the river in the area is reflected by the local channel bed elevation being "only about 21m above the base level of Lake Athabasca, 243 km downstream" (Rains and McKenna 1995). Lake Athabasca is in geologically stable Canadian Shield rock.

The Athabasca River has cut down to a stable channel (Kellerhals et al. 1972, pp.8-9). The tributaries of the Athabasca River, including the MacKay River, lag behind and are still downcutting. The future incision curve for the MacKay River will flatten out as the rate of channel incision decreases. Average rates of incision for the MacKay River over the past 9900 years are approximately 0.7cm/year. This figure is calculated using a maximum valley depth of 70m incised over a period of 9900 years. Rains and McKenna (1995) stated that a conservative estimate of present and future incision rates would be 0.2 to 0.3cm/year for the next 5000 years and that major changes in the course of the MacKay River are unlikely over the next thousand years.

Rains (1994) stated that a conservative estimate of average valley width expansion over the next 5000 years would be 90m or 2m/century (Rains and McKenna 1995). The maximum amount is estimated at 180m of valley-rim expansion on the outer edges of some eastern meanders. It is hard to predict the actual future rate of valley expansion because it is caused by two processes: the lateral migration of the river channel and landsliding. These estimates were calculated by measuring 55 valley widths (from rim to rim) where only a single reach of the active channel was intersected (Rains 1994). Rains and McKenna (1995) interpreted the long term trends of valley expansion based on the "winding down" of the river system using the average valley width to make their estimates.

Rains (1994) noted three small tributaries on the eastern side of the MacKay River valley that he designated as Creeks R, S and T (refer to Figure 2.2b). These creeks was characterized by small basins which was mainly wetlands dammed by beavers and "steep valley-wall gully channels" which "constitute the greater length of the creeks" (Rains 1994, p.20). These creeks have probably existed since the postglacial initiation of the MacKay River about 9.9ka BP (Rains 1994). The drainage basins for these creeks are small because the zonal drainage divide between the MacKay River and the eastern creeks that drain the Syncrude mine site is only a few hundred metres from the edge of the eastern side of the valley rim.

2.3.2 Slope Geomorphology of the lower MacKay River valley

Dusseault (1977) described the natural slope morphology, landsliding processes and geotechnical properties of the McMurray Formation oil sands. Dusseault (1977) stated that "natural slopes in the McMurray Formation are generally steep, slopes over 60m in height at an average slope angles of 55 degrees have been observed." The main conclusions of the thesis included:

- No deep-seated rotational failures could be found in intact oil sands,
- Natural slopes in the oil sands display high long-term strengths and
- Landsliding occurs at the base of slopes that have significant deposits of basal clays.

This work will be discussed in Chapter 5 that describes landslides in the McMurray Formation.

Chapter 3 Air photograph interpretation

3.1 Introduction

The new terrain analysis (Appendix B) was performed in 1995. It covers the lower 75km of the river valley which is shown in Figure 2.2b. Three sets of 1:10 000 scale air photographs are analyzed. The Syncrude October 15 to 18, 1991 air photographs and May 18, 1991 air photographs taken by Western Photogrammetry Limited cover the upper portions of the MacKay River. The Syncrude May 8 to 10, 1993 air photographs taken by Western Photogrammetry Limited cover the lower portions of the MacKay River. An enlarged portion of a 1:15 680 Alberta Forestry air survey (Alberta Photo Services, AS545 75) of 1953 is used to cover a small area outside the Syncrude leases 17 and 22. The prints were obtained from the Alberta Environmental Protection, Information Management Division in Edmonton (Alberta Photo Services).

The terrain analysis is divided into the air photograph patterns and the site symbols. Appendix B includes an explanation of the air photograph pattern symbol section of the terrain analysis and lists the site symbols used to distinguish features on the air photographs. Air photographs are referred to by their flight line and number (i.e., 17-717 denotes flight line 17, photograph 717). It is not necessary to distinguish the dates of the photographs since there is no overlap in numbering between the 1991 and 1993 flight lines. Appendix A contains a 1:100 000 map which shows the areas covered by the 1:10 000 air photographs.

This chapter is a discussion of the glacial and fluvial deposits and surface features in the MacKay River valley. The deposits and surface features are ordered from oldest to youngest in the following sections: 3.2) buried valleys, 3.3) river terraces, 3.4) oxbow lakes and 3.5) landslides.

The landslide inventory (Sections 3.5.1 to 3.5.9) includes the landslides in the valley in order from oldest to youngest deposit and the landslide sites selected for field investigations and monitoring. Figure 3.1.1 is a map of the study area that includes the position of the buried river valleys discussed in Section 3.2.

3.2 Buried valleys

3.2.1 Glacio-fluvial bedded sand and gravel channels

There are two buried river valleys that are of unknown age. These channels were filled with fluvial and/or glacio-fluvial deposits before the area was overtopped by Laurentide ice or during the glaciation. These channels are shown on Figure 3.1.1. Access to the channels is by canoe or helicopter at present.

Channel 1:

Channel 1, located on air photograph 13-459, is exposed in an outcrop about 120m long and up to 25m high that is parallel to the crest of the valley. The channel could possibly link with the Syncrude G-pit deposit (Figure 3.1.1). Both sides of the channel are flanked by a sandy Clearwater layer. The eastern contact with bedrock is a bouldery gravel with few fines. The boulders are derived from the cemented siltstones of the Clearwater Formation. The channel deposits fine from east to west into a cobbly gravel that grades into sand at the western end of the outcrop. Cobbles in the gravel are derived from the Canadian Shield and fractured, suggesting that the channel has been overridden by glaciers. The western contact with the Clearwater Formation sediments does not outcrop because it is covered with colluvium and vegetation.

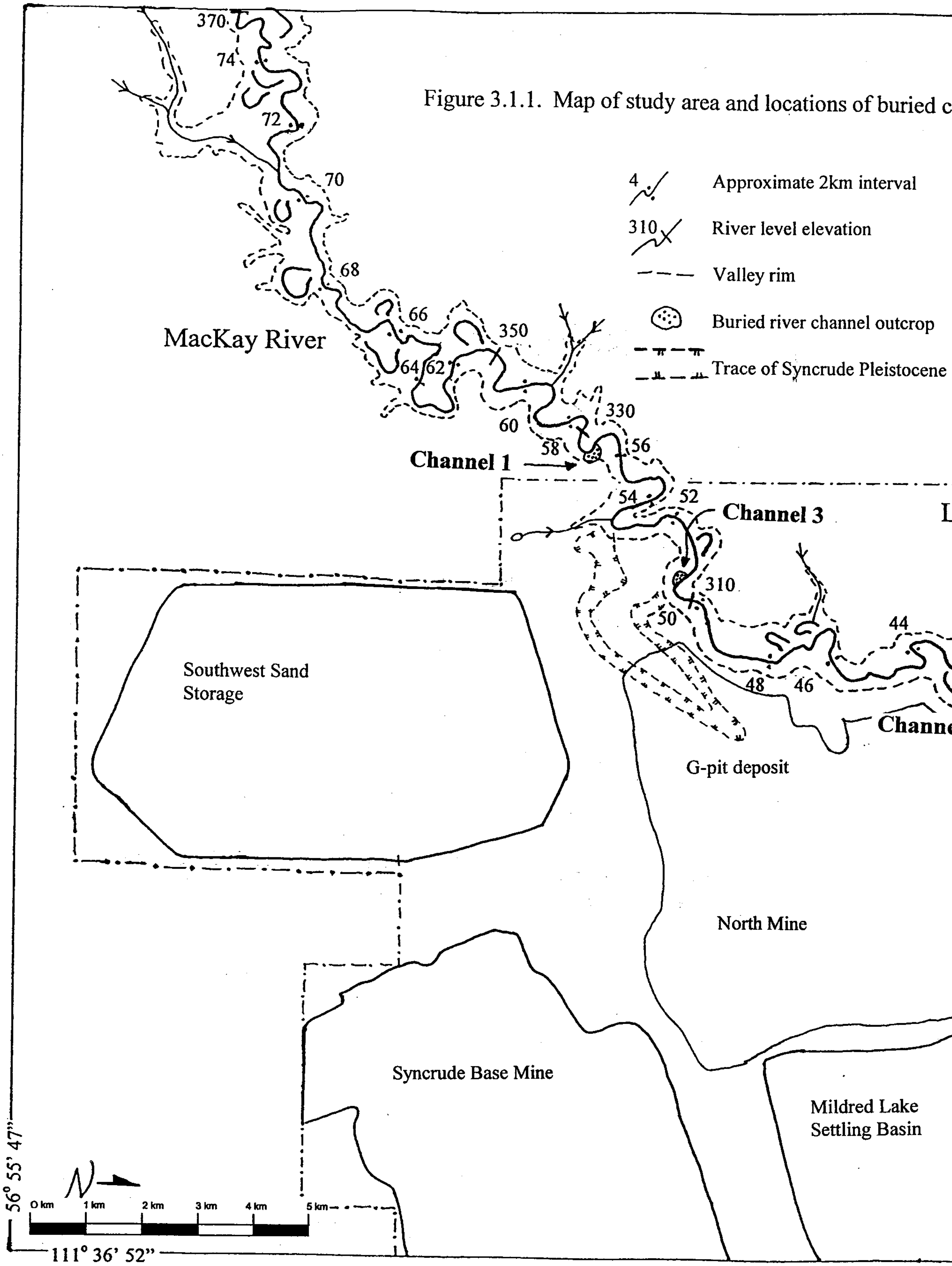


Figure 3.1.1. Map of study area and locations of buried c

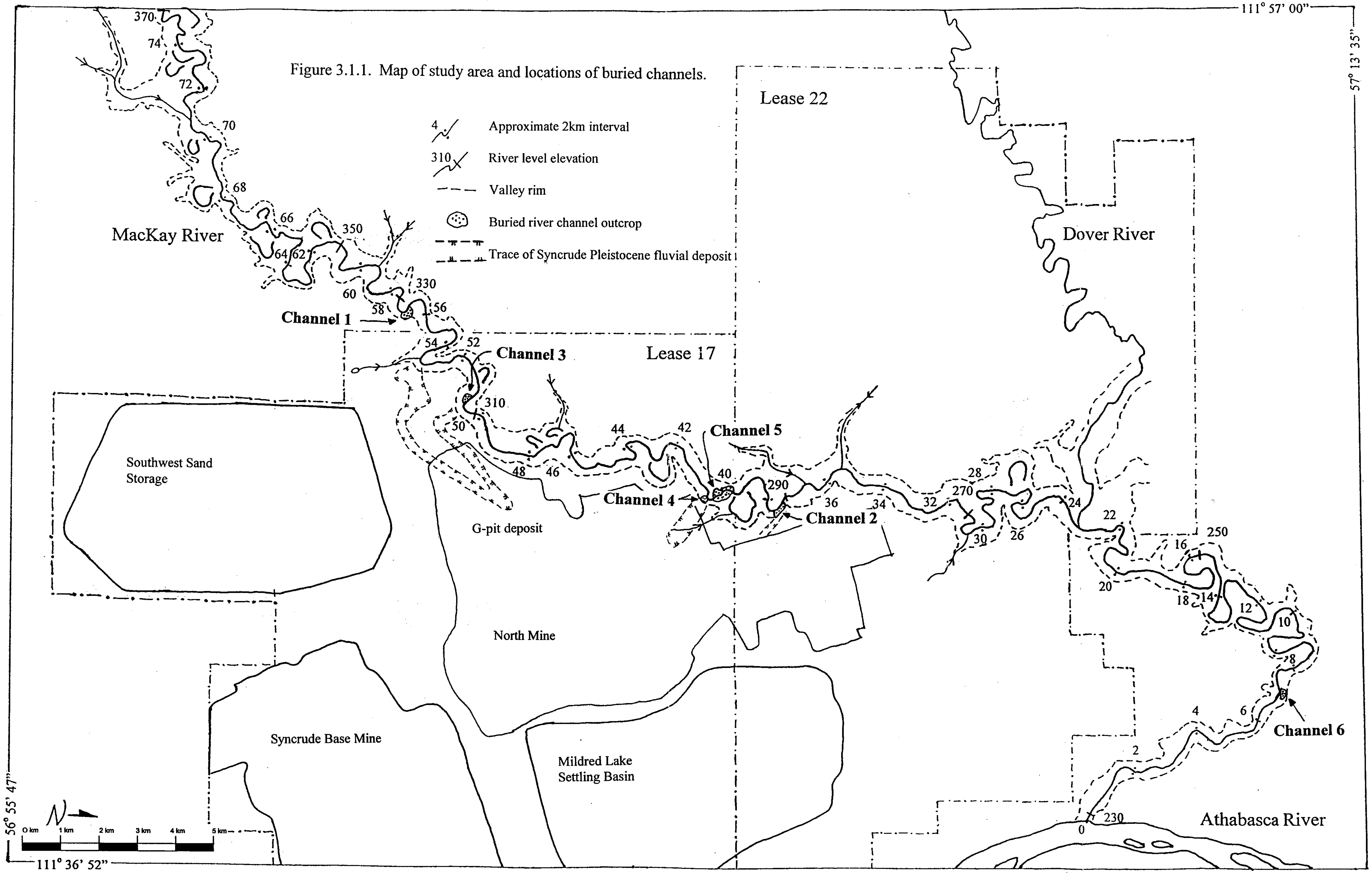


Figure 3.1.1. Map of study area and locations of buried channels.
Approximate 2km interval
River level elevation
Valley rim
Buried river channel outcrop
Trace of Syncrude Pleistocene fluvial deposit
MacKay River
Dover River
Athabasca River
Lease 22
Lease 17
Channel 1
Channel 2
Channel 3
Channel 4
Channel 5
Channel 6
Southwest Sand Storage
G-pit deposit
North Mine
Syncrude Base Mine
Mildred Lake Settling Basin
111° 57' 00"
57° 13' 35"
56° 55' 47"
111° 36' 52"
0 km 1 km 2 km 3 km 4 km 5 km

The mean slope angle of the deposit is 55 degrees with some areas standing near vertical. The dip and dip direction of the cross-bedding within the channel averages 36 degrees towards 267 degrees. I believe that the related flow was from north to south, intersecting the present river channel at right angles, based on an interpretation of the cross-bedding structure. The continuation of Channel 1 was not found on the west side of the MacKay River valley in field visits and on the air photographs because the slope is covered in colluvium and vegetation.

Channel 2:

Channel 2 is located directly downstream from slide 17-617a on air photograph 17-617. The southern end of the channel is flanked by sandy Clearwater Formation bedrock. Figure 3.2.1a shows the area around the buried river channel on an overlay of air photograph 17-617. The deposit grades from a bouldery gravel to a cobbly gravel, then to a gravel along a steep scarp from the edge of the channel towards the northwest. The outcrop of bouldery gravel is about 25m long, the outcrop of cobbly gravel is about 20m long and the outcrop of gravel is about 10m long. The gravel grades into a medium to fine sand deposit that outcrops for 100m until the channel disappears under colluvium and vegetation. The channel reappears 60m downstream where there is an outcrop of gravel along the river edge that continues for 60m. The gravel deposits contain pebbles and cobbles derived from the Canadian Shield and are cryoturbated in some areas. Fractures in the pebbles and cobbles suggest that the gravel has been put under large stresses by the glaciation. In some areas the gravel is lightly cemented by what is believed to be silica. The cement is weak giving the gravel a cohesion of no more than 5 to 10kPa. Successive sequences of gravel fining upwards to sand are present showing that the deposit was laid down in a series of flow pulses. Figure 3.2.1b is a photograph of

Legend

- Rounded scarp
- Sharp scarp
- Rounded break in slope, convex
- Rounded break in slope, concave
- Slope angle
- Steep slope over 45°
- Terrace

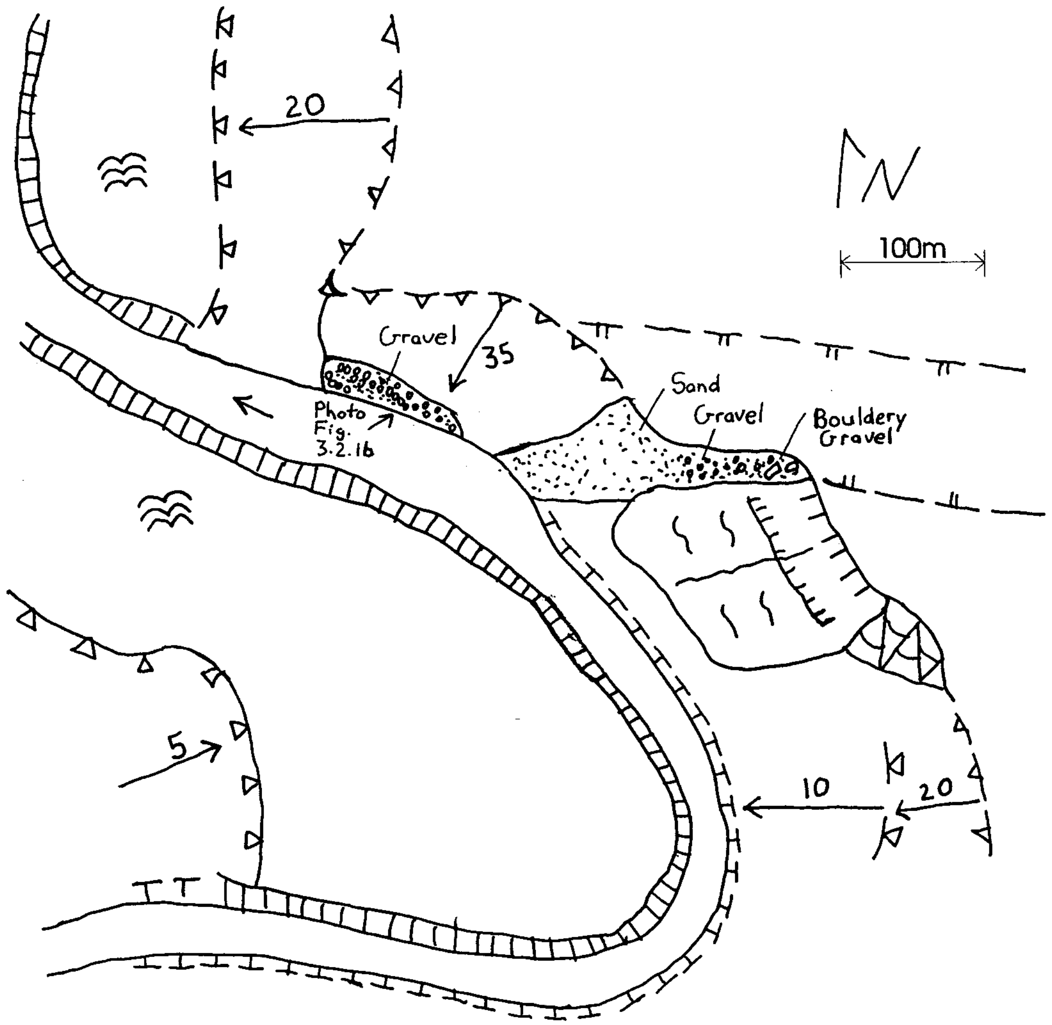


Figure 3.2.1a. Area around buried Channel 2.

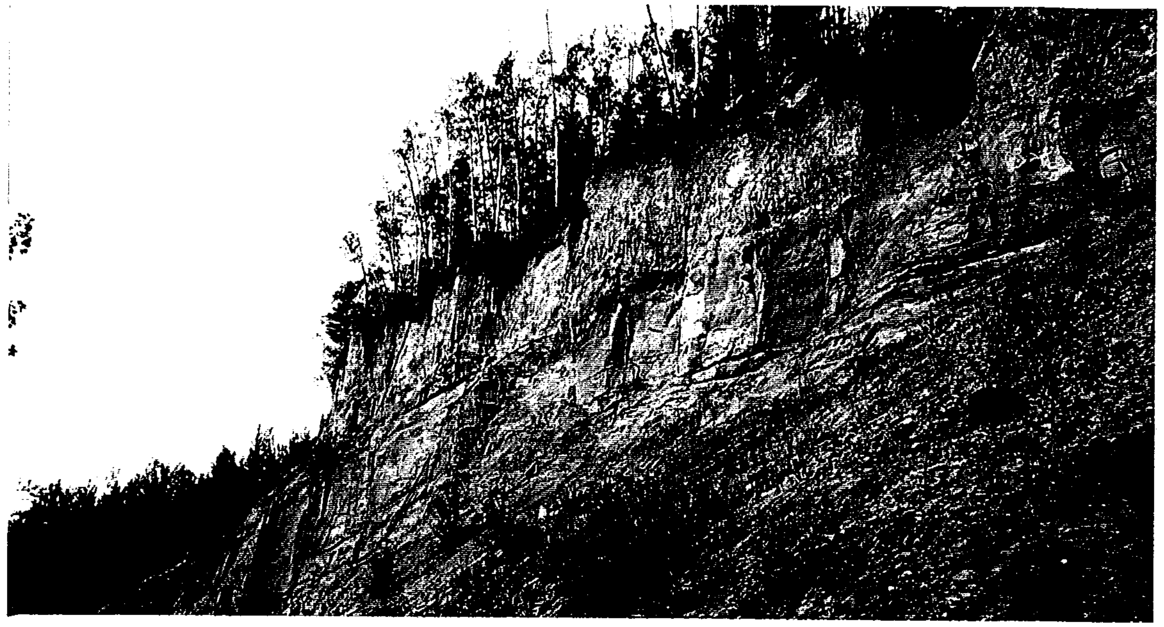


Figure 3.2.1b Photograph of the sand outcrops in the centre of Channel 2 that are below 5m of glacio-lacustrine deposits.

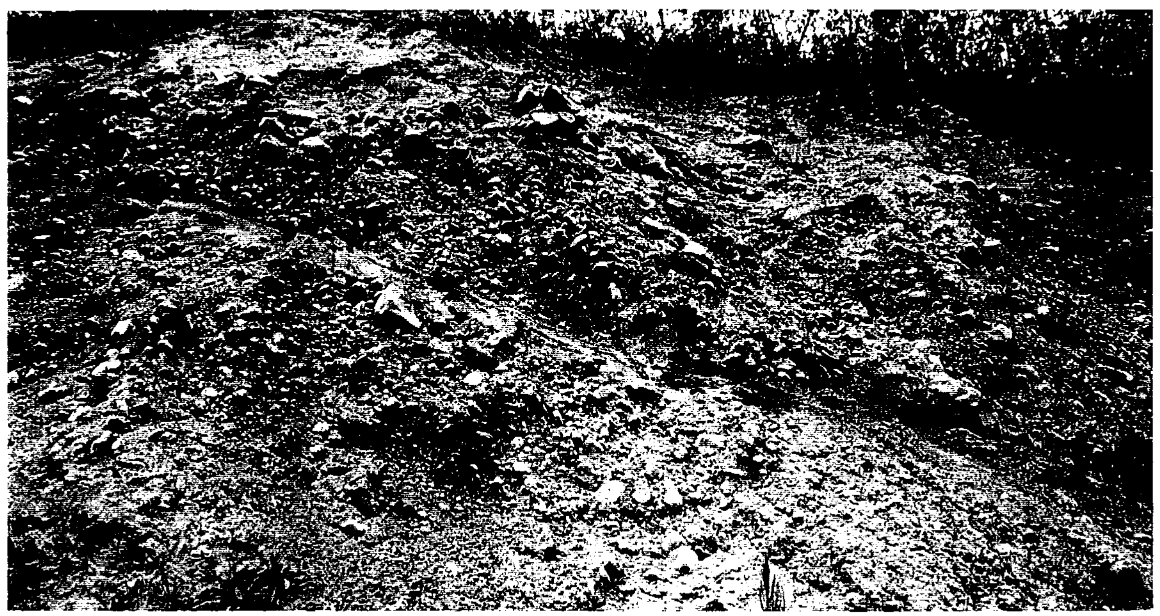


Figure 3.2.1c. Photograph of the gravel deposits of Channel 2. Figure 3.2.1.a. shows the location of the outcrop. The outcrop is 5m high for scale.

the sand and gravel sequences at the edge of the channel and Figure 3.2.1c is a photograph of the medium to fine sand layers in the centre of the channel. There are only glacio-lacustrine sediments overlying the channel.

The sand deposits stand nearly vertically and the slope angles of the gravels range from 40 to 70 degrees. The layering in the sand in the southeast has an average dip and dip direction of 17 degrees toward 340 degrees. The layering in the northwest gravel has a dip and dip direction of 26 degrees toward 160 degrees. This indicates that measurements were taken on either side of the channel which runs along an azimuth of 70 degrees, approximately parallel to the current river channel.

The channel outcrop was unknown prior to the present study. I do not know where the channel is on the other side of the river because it is hidden by the blanket of glacial sediments that cover the area. The width of the channel perpendicular to the line of the thalweg is about 60m, therefore it is possible that the grid of boreholes Syncrude has drilled to the east of the channel at a 1200m spacing does not intersect the channel. On the western side of the river valley it is possible that Channel 2 continues along a stream (refer to Figure 3.1.1) that flows into the MacKay River valley. The profile of the stream is much flatter than the profiles of streams R,S and T (discussed in Section 2.3.1) indicating that it is possibly incised into a sand or gravel rather than the Clearwater Formation sediments.

Discussion:

These channels both have Shield pebble deposits. The Clearwater Formation deposits the channels are incised into are quite sandy and were not found in outcrop at any other site along the MacKay River valley. Both channels have Canadian Shield derived cobbles that were possibly fractured by the stresses imposed during glaciation. Babcock et al. (1977) suggested that a possible mechanism for the fracturing of the cobbles is shear forces caused by glacial drag. The Canadian Shield is 250 km north of the MacKay River, therefore the cobbles could not have been transported by non-glacial rivers because the drainage in the region is to the north (Klassen 1989). These deposits are not Saskatchewan gravels and sands (deposited by preglacial rivers) because they have Shield pebbles (Stalker 1968).

I have not taken actual field measurements of the contact angles between the channel walls and the Clearwater Formation, but estimate that the contacts are steeper than 30 degrees from photographs. The steepness of the channel walls could be a result of the strength of the material the channel is incised into because the slopes in some areas of the MacKay River incised into the Clearwater Formation are steeper than 40 degrees (refer to Section 3.3.1)

The channel sediments are possibly glacio-fluvial deposits from the Livingstone Lake megaflood. The preglacial MacKay River valley that drained the area could have acted as a preferential pathway for the south flowing flood waters. Rains et al. (1993, p.323) show in their Figure 1 that the path of the Livingstone Lake megaflood flowed through Syncrude Leases 17 and 22.

The buried channels could act as seepage pathways for tailings water if containment structures are built near them. The sandy portions of the channel outcrops could be used as natural analogs for sand reclamation on the Syncrude mine site. Natural vegetative cover and erosion rates would be of particular interest.

3.2.2 Other buried channels

There are four channels outcropping along the MacKay River valley that were active before or during the late Wisconsinan glaciation. Channels 3, 4 and 6 were possibly part of the hypothesized, Late Wisconsinan, Livingstone Lake megaflood (18000 years BP, Rains et al. 1993). These channels are shown on Figure 3.1.1. Currently, access to Channels 3 to 5 is by helicopter or canoe. Channel 6 is accessible via a forestry road which continues past the Fort MacKay landfill.

Channel 3:

Channel 3 is located on air photograph 13-461 and is possibly part of the Syncrude G-deposit that was mapped by Syncrude geologists with borehole data from the Syncrude borehole library. The outcrop is 40m long and consists of a 3m high outcrop of sand and gravel with imbricated cobbles overlain by till. No paleoflow direction was noted in field investigations. The till has filled a preglacial channel that is incised into the Kce Member of the Clearwater Formation at river level. Ferguson (1995) discovered this channel. I have not visited this area.

Channel 4:

Channel 4 is located on air photograph 16-575 and is possibly part of the buried valley filled with glacio-fluvial deposits that Syncrude has mapped from borehole data. The channel is shown in Syncrude Production Drawings, Mine Development, Lease Geology Drawings SCL-GEO-OB/89-02-18/23 and SCL-GEO-OB/89-02-19/23 (1989) in company documents. The channel is located between two small translational landslides. The outcrop is a sharp, steep-sided (approximately 55 degrees) point 30 metres high jutting out into the river valley between the two translational landslides. The total length of the outcrop is approximately 40 metres.

The deposit cannot be identified as a specific unit according to the Syncrude classification (Lobb and McMullin 1989). The grain size distribution of the deposits is similar to the Syncrude Pf_{5b} unit because it is a bouldery sandy gravel with few fines, but it cannot be classified as a fluvial deposit because the deposit has no sedimentary structure visible. The boulders in the outcrop were from local sources and were not derived from the Canadian Shield. Blocks of cemented Clearwater siltstone up to 32 m^3 in volume and 2m thick and boulders of McMurray oil sands up to 2 m^3 in volume are found in the outcrop. The pieces of McMurray oil sands indicate that the deposit is locally derived since McMurray oil sands clasts do not survive much transportation in a fluvial environment. The cobbles and boulders within the deposit are not fractured indicating that they were under less stress than the deposits of the preglacial buried river valleys discussed in Section 3.2.1. Logs from Syncrude borehole 43-48-00 indicated that this deposit was a Pf_{5a} fluvial deposit which has no boulders. The most probable explanation for this discrepancy is that the drilling did not recover any of the boulders and disturbs the samples, so no structural data can be obtained.

The channel could be part of the preglacial drainage system that flowed through the area that was infilled with outwash sands before or after glaciation. The deposits in the channel can not be till because they are not deposited directly by ice. Channel 4 deposits are different from all the other glacial deposits in the area and warrant further investigation.

The neck cut-off, steepened gradient and sharp bend in the river channel are caused by Channel 4 deposits. Large boulders from the glacial deposit armoured the river banks and channel as the river cut down into the deposit. There are many Clearwater-derived boulders lining the outside of the river channel. Most of the river flow in the neck cut-off is between two of these large boulders that are much larger than the boulders found in the channel deposits. The neck cut-off is directly below the Channel 4 outcrop to the southwest.

Channel 5:

Channel 5 starts 100 metres downstream of Channel 4 and also appears to be part of the MacKay River outcropping of the fluvial channel mapped by Syncrude in the area. Channel 5 outcrops for 800m on both sides of the MacKay River from water level to the top of a 8m terrace (see air photographs 16-575 and 17-615). The till outcrops up to 25 m above river level behind the terrace 50 m downstream from Channel 4.

The glacial deposit has the same grain size distribution as the Pf_{5a} Pleistocene fluvial deposit since there are no boulders in the deposit (Lobb and McMullin 1989) and it is a pinkish-gray gravelly sand with under 5 percent fines (passes through 0.062mm sieve) and an average pebble size of approximately 4cm in the largest dimension. The deposit should not be classified as a Pf_{5a} because it has no sedimentary structure. The pebbles and cobbles are derived exclusively from the Canadian Shield. There are no boulders observed in any of the outcrops. Rip-up clasts of till are present in the sediments indicating that it could have been deposited during the Lake Livingstone megaflood. Figure 3.2.2a is a photograph of a rip-up clast of till in the pebbly sand and Figure 3.2.2b is a photograph of the Channel 5 deposits taken from river level. Channel 5 is deposited on Kcw member of the Clearwater bedrock and possibly on top of the McMurray Formation oil sands in the northern most outcrops.

The Channel 5 deposits are much finer than the Channel 4 deposits and contain no boulders, but have pebbles and cobbles derived from the Canadian shield. It outcrops for up to 25m above river level, as opposed to Channel 4 that outcrops from the beneath the crest of the valley down for 25m. The two channels are at nearly the same position, therefore Channel 5 should be older than Channel 4 because it is lower in the geologic sequence, although it cannot be shown that Channel 4 cross-cuts Channel 5 because of the river valley. Pebbles derived from Canadian Shield rock are not fractured because there is no contact between the clasts. The sand in the deposit shows no signs of cementation. I believe that the sediments in Channel 5 was deposited during the Lake Livingstone megaflood.

The river drops 5 m over the 1 km in this reach of channel cut into the glacio-fluvial deposits. The gradient is steep because the river is incised into the erosion-resistant Kcw and McMurray Formation oil sands and the channel and banks are armoured with pebbles and cobbles from the channel deposits. It is three times the average gradient of 1.6m per km for the first 80km of the MacKay River.

Channel 6:

Channel 6 (air photograph 23-813) is visible in outcrop for 100m along the crest of the valley and for 7m down from the top of the scarp. The glacial deposit stands at 60 degrees and has the same grain size distribution as a Syncrude Pf_{5a} fluvial deposit (Lobb and McMullin 1989). It is similar in lithology to the Channel 5 glacio-fluvial deposits, but has approximately 20 percent fines. Channel 6 was also probably formed during the Livingstone Lake megaflood

Figure 3.2.2a. Photograph of rip-up clast of till in gravelly sand of Channel 5. The head of the rock hammer marks the contact.

Figure 3.3.2b. Photograph of the Channel 5 glacio-fluvial sediments from river level.

3.3 River terraces

Terraces are unevenly distributed along the river valley in the study area. The river is divided into 5 sections based on the size and frequency of terraces and the bedrock the river is incised into. Table 3.3.1 is a summary of these sections. Figure 3.3.1a shows the location of these terraces in the MacKay River valley. The terraces are shown in more detail in the air photograph interpretation in Appendix B. The heights of the terraces are determined through air photograph interpretation and were verified whenever possible during field work.

Appendix D contains the raw data used to compile Table 3.3.1 . The terraces measured are along sections of the active river channel and include only the length of active riverbank that the oxbow lake sections border. The terraces on these oxbow lakes are 15 to 20m above river level and correspond to the second level of terraces discussed later in this section.

Table 3.3.1 River terraces along the MacKay River valley.

Section	Position in km from mouth of river	Percent of bank terraced	Oxbow lakes	Maximum terrace width (m)	Bedrock in section at river level
1	0 to 22	26	0	500	Waterways Formation
2	22 to 38	60	1	500	McMurray Formation
3	38 to 54	66	4	450	Clearwater Formation
4	54 to 62	67	1	310	Clearwater Formation
5	62 to 80	51	8	750	Clearwater Formation

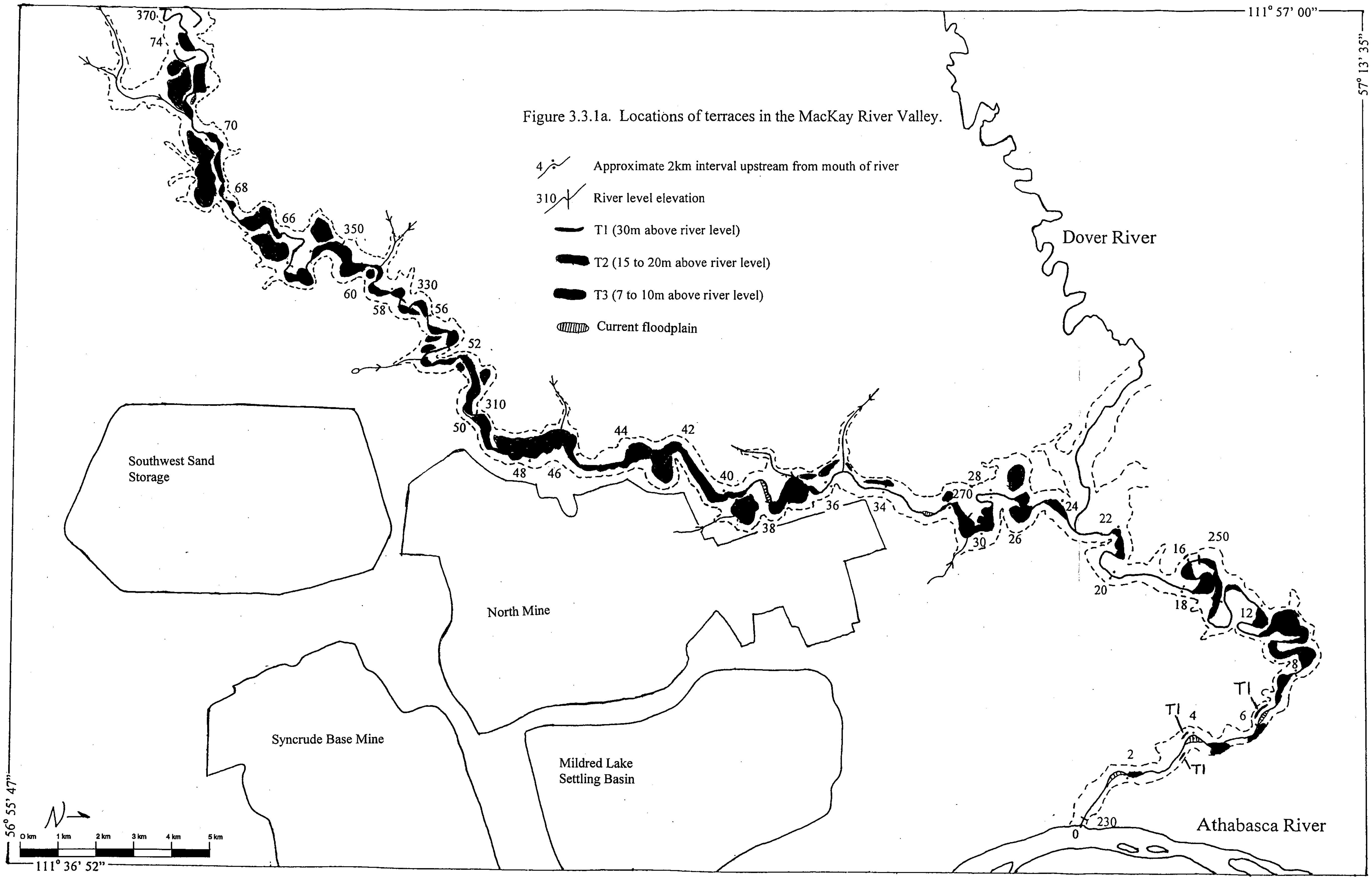


Figure 3.3.1a. Locations of terraces in the MacKay River Valley.
Approximate 2km interval upstream from mouth of river
River level elevation
T1 (30m above river level)
T2 (15 to 20m above river level)
T3 (7 to 10m above river level)
Current floodplain
Dover River
Athabasca River
Southwest Sand Storage
North Mine
Syncrude Base Mine
Mildred Lake Settling Basin
111° 57' 00"
57° 13' 35"
56° 55' 47"
111° 36' 52"
N
0 km
1 km
2 km
3 km
4 km
5 km

There are few terraces in Section 1 because the river is incised into the Waterways Formation limestone that forms slopes that are more stable than the other formations. This section of river was rapidly eroded because the limestone goes into solution and the quartz particles eroded off the McMurray Formation are extremely abrasive. The upper 3 to 6m of the Waterways Formation is an easily eroded argillaceous limestone that is heavily jointed. Section 2 of the river is incised into the McMurray Formation and contains only one oxbow lake because the material forming the slopes is very strong. The locked sands (Dusseault 1977) in the McMurray Formation can contain bitumen that acts as a bonding agent and an impermeable layer that slows erosion. Section 3 is incised into shallow slope-forming members of the Clearwater Formation and contains 4 oxbow lakes. The river has the highest gradient in Section 3 because of the armour of Shield clasts from buried Channels 2, 4 and 5. Section 4 has a narrow valley and few large terraces because the upper Kcc and Kcd Clearwater Members are quite strong since slopes stand at up to 55 degrees. Most of the terraces in this section are less than 200m wide. Section 5 has frequent, large remnant terraces and 8 oxbow lakes because the river is cut into weak material that forms shallow slopes. There is no correlation between the erosional resistance of the material the river is incised into and the size and frequency of terraces, but there is a inverse correlation between the strength of the material forming the slopes and the size and frequency of terraces. Sections 3 and 5 are both in easily eroded material, but Section 5 has twice the frequency of terraces that tend to be much larger than the terraces in Section 2 (refer to Appendix D).

There are 3 levels of terraces in the MacKay River valley. Rains (1994) found only one level of terrace from air photograph and orthophotograph interpretation. The oldest terrace (T1) is at 30m elevation above river level. Only one outcrop of this terrace was found during field investigations at km 8 of the river (refer to Chapter 5, Slide 22-773f) because the canoe reconnaissance concentrated on the landslide sites and features closer to river level. The T1 terrace does not exist in Sections 3, 4 and 5 because the valley heights are from 30 to 45 metres and any sign of the terrace would be wiped out by valley widening as the young MacKay River cut its channel. It is difficult to distinguish the highest terrace from possible landslide scarps in Section 2 because the upper portions of the valley slope are thickly vegetated and there are only 2 terraces preserved in Section 1. The oldest terrace is probably an erosional strath terrace and is never paired with an equivalent terrace across the valley. Therefore, the oldest terrace (T1) does not represent a phase of relative channel-floodplain stability.

The second terrace (T2) is at 15 to 20m above river level. This terrace is present in all sections of the river valley and was reported by Rains and McKenna (1995). The third terrace (T3) is at an elevation of 7 to 10 metres and is well-preserved along all sections of the river except Section 1. Figure 3.3.1b is a photograph of the deposits in a T3 terrace. This terrace is easily identified by the 5 m sequence of gravels fining upwards into sands then silty sands. At river level, the current flood plain surfaces are rarely over 30m in width because the river is actively downcutting. Figure 3.3.1c shows a profile of the river valley with the positions of the terraces. The heights of the T2 and T3 terraces are plotted at 20 and 10m above the river, although the heights individual terraces were not measured during field investigations. More detailed cross sections of the river can be found in Rains (1994) and Rains and McKenna (1995).

The ages of the terraces are unknown. During field visits to the terraces, no organic debris was found to carbon date. More of the river terrace remnants are on the eastern side of the river valley, therefore Rains (1994) concluded that it is probable that the river has in part preferentially migrated west or northwest.

Figure 3.3.1b. Photograph of the fluvial terrace deposits from the 7 to 10m terrace (T3).

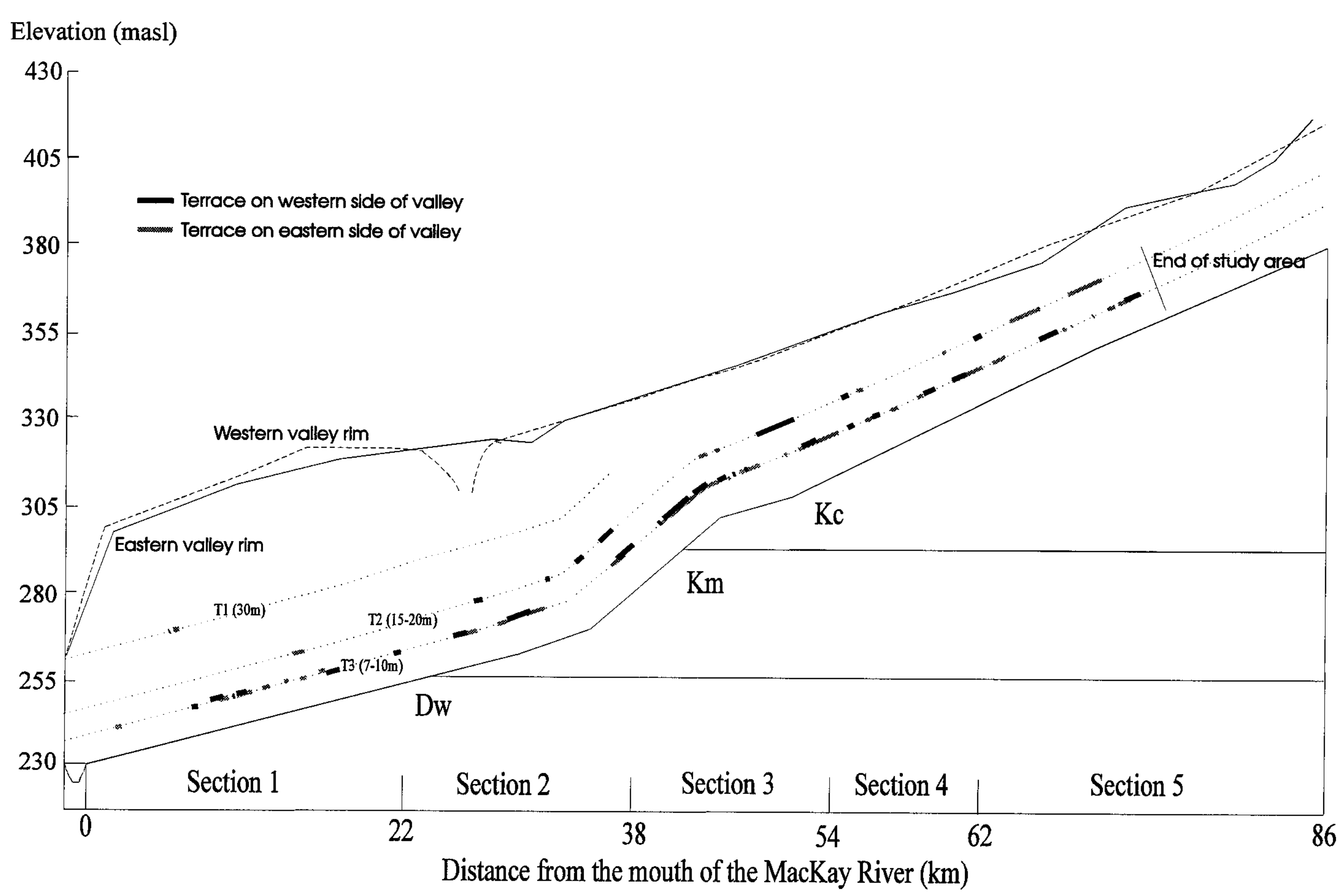


Figure 3.3.1c. The position of terraces on river profile (modified from Rains 1994, Fig.8, p.22)

3.4 Oxbow lakes

There are 14 oxbow lakes in the first 80km of the MacKay River valley. Figure 3.1.1. shows the oxbow lakes along the MacKay River. These oxbow lakes range in length from 500m to 1500m and are concentrated in areas where the erosional resistance of the bedrock is low and slopes are less than 30 degrees. There are no oxbow lakes in Section 1 and only one oxbow lake in both Sections 2 and 4. Sections 3 and 5 are in relatively weak Clearwater Formation members and have 4 and 8 oxbow lakes respectively. Therefore, there is an inverse correlation between the strength of the material forming the valley walls and the number of oxbow lakes in a section (refer to Table 3.3.1).

The most recent oxbow cut-off occurred between October, 1954 and September, 1967. This range of dates was obtained from Maps Alberta air photographs AS547 100 and AS964 160. This range of dates was later narrowed to between 1957 and 1967 with the aid of an air photograph of unidentified origin found in storage files at Syncrude Canada Limited. This cut-off is a result of the river re-routing itself through Channel 3 of the pre-glacially active river channels discussed in Section 3.2.2. The glacio-fluvial deposit between the two channel bends was approximately 40m thick in 1954. In 1957, 6m of this material was eroded off each side of the deposit slope. I estimate that the river eroded a total of 4m/yr off both sides of the wall. This is very approximate because:

1. The exact date of the air photo taken in 1957 is unknown. I believe that it was taken in fall because of the appearance of the vegetation,

2. The distances scaled from the air photographs are no more than 3mm because of the small scale of the air photographs and there are shadows on the north side of the wall in both air photographs. Any error in measuring these small distances leads to error in the estimate. It would have been preferable to have air photographs with a larger scale than 1:16 000 and 1:32 000 for the 1954 and 1957 air photographs respectively and

3. There are errors in scaling distances off air photographs. The scale of the air photograph decreases from the center to the edges. The wall was positioned at different locations relative to the centre of each air photograph.

The river channel had cut through the wall by 1967. The estimated date of the break-through is 1964. This is calculated by dividing the 40m thickness of the wall by 4m/yr. The estimate is approximate because there was a variation in the annual precipitation from 1957 to 1967. The annual precipitation in 1958 and 1961 to 1965 was below the mean from 1953 to 1992 and the annual precipitation in 1959, 1960 and 1966 was above the mean (Environment Canada 1994, *refer to* Figure 4.2.2c). It is possible that break-through occurred in 1960 or 1966 because of the high rainfall during these years. The channel appears to have been flowing through the new portion of the river for least a year because in the 1967 air photograph the new portion of the channel is almost the same width as the older portions of the channel and the abandoned section of the river is drained in some areas. Rains and McKenna (1995) predicted that the worst case possible migration of a channel bend incised into the bedrock would be 180m over 5000 years or 0.036m/yr. The predicted maximum rate of migration is 50 times less than the rate of migration observed in the glacio-fluvial deposits (2m/yr).

Candidates for future cut-offs are at 8, 16 and 19 km upstream from the mouth of the river. All three would be in the Waterways Formation in Region 1, which has no oxbow lake cut-offs at present.

The most recent cut-off and the probable future cut-offs, support Rains' (1994) hypothesis that Sections 1 to 4 have migrated to the west or northwest during the Holocene because the abandoned lakes are on the east and southeast side of the river valley. Another factor supporting the migration of the river to the west or northwest is the overall shape of the river channel. Figure 3.3.1a shows that the lower 40 km of river curves clockwise around the bottom of Lease 22

3.5 Landslide Inventory

3.5.1 Introduction

There are 136 landslides identified in the study area of the MacKay River valley. The landslide inventory is in Appendix C and the landslides are marked in the site symbols section of the terrain analysis in Appendix B.

The following criteria are used to select landslides shown in the terrain analysis:

1. The landslide is readily visible on the air photograph and

2. The landslide has a scarp width of greater than 40m or 4mm on a 1:10 000 scale air photograph. Landslides narrower than 40m are noted in the site symbols section of the terrain analysis, but are not included in the landslide inventory. The small landslides are not included in the inventory because it is difficult to distinguish them at such a small scale and any attempt to document them would be incomplete.

Landslides are identified by the number of the air photograph they appear on and a letter to denote their position on the river. The landslides are lettered sequentially downstream (i.e. landslide 17-617b is the second landslide on air photograph 17-617).

In 11 cases there are several small landslides on a slope, not large enough to be considered in the landslide inventory, so they are grouped together as larger slides. The comments section of the landslide inventory records when slides are groups of successive slides. The slides are adjacent to each other on the valley rim and always have the same mode of movement in the same material.

Most of landslides involved only type of soil or bedrock unit. These units are: the McMurray Formation, the Clearwater Formation, the Pleistocene glacial sediments, the river terrace deposits and the colluvium. There were no landslides in the Waterways Formation large enough to be recorded in the landslide inventory. The geologic units displaced by the slides are noted in the unit column of the landslide inventory.

There are sixty-six landslides displacing the McMurray Formation, sixty-seven landslides displacing the Clearwater Formation, sixteen landslides displacing the Pleistocene deposits and six landslides displacing the river valley deposits. Twenty-five landslides on the MacKay River involve either the Clearwater Formation and Pleistocene units or the McMurray Formation and the river terrace deposits.

Incidence

Approximately 15 km of the 115 km or 13 percent of the river valley rim have active or dormant landslides. "Active landslides are currently moving" and dormant landslides are "landslides which have last moved more than one annual cycle of seasons ago", but "the causes of movement apparently remain" (Cruden and Varnes 1996). The active landslides are concentrated in the slopes above river bends, especially in the high-sinuousity lower reaches from km 6 to 30. Another 5km of the river valley has relict or abandoned landslides, but it is probable that this figure is underestimated because most movements in the river valley are shallow and hidden by overgrowth. Landslides are abandoned when "the river which has been eroding the toe of the moving slope has itself changed course" (Cruden and Varnes 1996). Relict landslides "have clearly developed under different geomorphic or climatic conditions" (Cruden and Varnes 1996). These figures are estimated from the crest widths of landslides included in Appendix C. The percent of slopes with active or dormant landslides should decrease over time as the gradient of the lower reaches decreases as the MacKay River cuts down to a stable channel. I make this statement without considering the possible future impacts of mining operations near the MacKay River valley.

Frequency

Air photographs from 1953 and 1991 look similar. Active shallow movements on slopes above bends in the river channel appear to be identical in 1953 and 1991 with few exceptions. There have been 2 larger (over $5x10^4m^3$) movements between 1953 and 1991. The movements are a translational earth-slide (Slide 16-617a, Chapter 4) and a retrogressive rotational earth-slide earth-flow (Slide 23-806c, Chapter 6). The surface of rupture of both movements is in the lower members of the Clearwater Formation. I estimate that there is a movement displacing over $5x10^4m^3$ of material every 25 years. The frequency of movements between $5x10^4m^3$ and $5x10^3m^3$ is approximately 1 movement every 5 years. Movements smaller than $5x10^3m^3$ occur every year, but the frequency is dependent on the amount and intensity of precipitation. There is no evidence of any movements over $1x10^6m^3$ ever occurring in the river valley.

Period landslide is active (duration)

The time a landslide remains active is related to the rate of retreat of the crown of the landslide. The slower the rate, the longer it takes the slope to reach a stable angle. The larger movements, including the retrogressive rotational earth-slide earth-flows (Chapter 6) and translational earth-slides (Chapter 4), are probably active for 50 years, but the landslides can be re-activated by toe erosion. Most landslides in the valley are active for much larger periods of time. The rock topple and rock slides in the McMurray Formation oil sands and the shallow earth-slide earth-flows in the Clearwater Formation sediments are active in the 1953 air photographs and in the 1991 air photographs and appear similar. It is probable that these landslides have been active for hundreds or thousands of years.

3.5.2 Landslides in the Waterways Formation

The mode of landsliding found in the limestone is rock falls. The rock falls are caused by the river eroding mudstone in the formation, undercutting limestone layers. The rock falls are not visible on the 1:10 000 scale air photographs and are only visible through field observation, therefore the inventory does not include any rock falls. Figure 3.5.2a shows a rock fall 100m downstream from the zone of accumulation of Slide 22-773f. Figure 3.5.2b is the section of the cliff the block fell from.

There are 4 sets of joints in the Waterways Formation (Babcock 1975). They dip within 15 degrees of vertical and strike north-south, east-west, northeast-southwest and northwest-southeast. Either the first two sets or the last two sets are found together at a particular limestone outcrop. These joints form rectangular blocks when combined with the flat-lying bedding surfaces.

The strong, sparsely jointed layers of the Waterways limestone along the river form vertical cliffs up to 20m high and weak mudstones have an angle of repose similar to a coarse gravel (Craig 1984) because it is heavily jointed (Babcock 1975). These joints form pebble-sized cubes which average $4cm^3$ in volume.

The paleosol above the limestone has not been a factor in recent landslides along the lower reaches of the MacKay River. This statement is based on observations of the surfaces of rupture and styles of movement from sites with paleosols that I have visited (Landslides 22-773 c, d, e and f), although it is possible that there are buried landslides that moved along a paleosol layer. The paleosol should not be confused with the basal clays that are above the paleosol and part of the McMurray Formation (Figure 2.2a).

Figure 3.5.2a. Rock fall in the Waterways Formation. The black dot marks the same location on Figures 3.5.2a and b. Philip Lobo is in the photograph for scale.

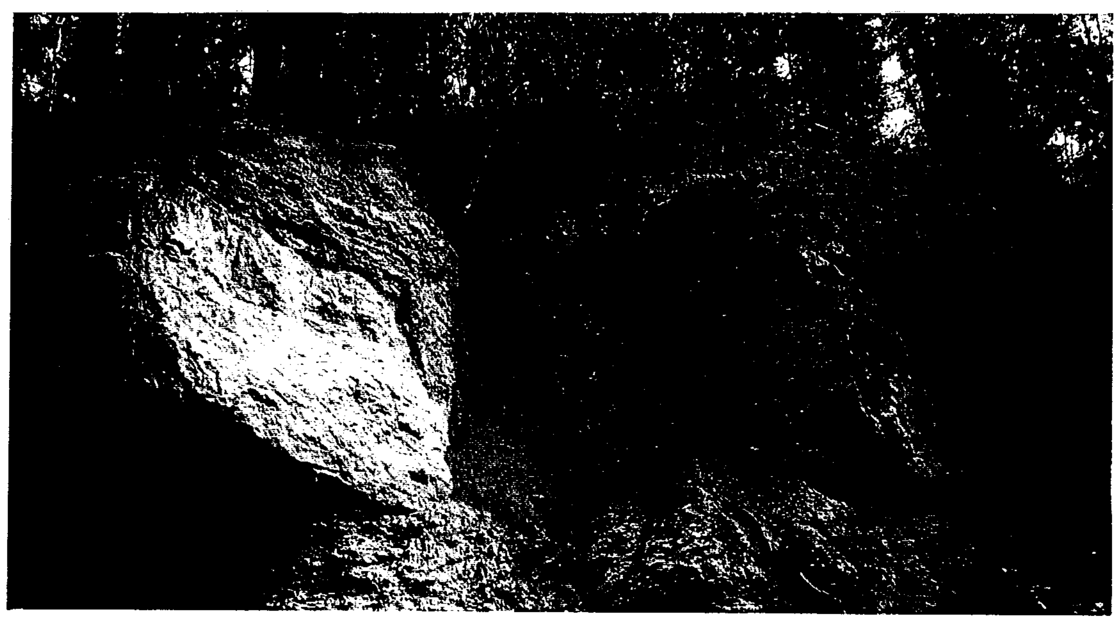


Figure 3.5.2b. The section of cliff the block fell from. The vertical field of view is approximately 4m for scale.

3.5.3 Landslides in the McMurray Formation

Natural slopes in the oil sands of the McMurray Formation move by shallow sliding or complex rock topples and rock slides. Exfoliation fractures parallel to the slope face (Babcock 1975) are a large factor in these landslides. The marine sands at the top of the slopes form vertical cliffs. The exfoliation fractures parallel to the face of the slope create rectangular blocks that topple, then break up into debris and roll down the slope. Debris either accumulates on a terrace or rolls into the river and is washed away. The slopes below the marine sands have an average angle of 40 degrees. The exfoliation fractures parallel to the surface of the slope allow blocks of sandstone to detach and roll down the slope.

Basal clays at the base of the McMurray Formation cause retrogressive shallow earth-slides earth-flows at Landslide sites 17-773 c, d and e. The clays exposed at the face of the slope soften and move as shallow rotational slides, then the material loses strength and flows down the slope. The term basal clay is employed (Dusseault and Scafe 1979) to designate the overbank and pond muds that are in the oldest member of the McMurray Formation.

The terrain analysis and site visits show that the angle of actively eroded slopes in the McMurray Formation is from 35 to 45 degrees with an average slope angle of approximately 40 degrees. The actual angle can vary between 30 degrees and 90 degrees depending on the strength, cementation and bitumen content of individual layers within the formation. The ultimate angle of the slopes in basal clays cannot be estimated as there were no abandoned basal clay slopes found during field investigations, although it is probable that they exist. The angle of the profiles of Slides 22-773c, d and e is about 15 degrees.

There is no evidence of any deep-seated movements in the oil sands. The modes of movement in the McMurray Formation along the MacKay River Valley are discussed in Chapter 5.

3.5.4 Landslides in the Clearwater Formation

There are 3 types of landslides in the Clearwater Formation: translational earth-slides, rotational earth-slide earth-flows and retrogressive shallow earth-slide earth-flows. These landslide modes are discussed in Chapters 4, 6 and 7 respectively.

The angles of Clearwater Formation slopes in the MacKay River valley are quite variable. The angle is a function of the modes of movement and the lithology within an individual member of the Clearwater Formation. Generally, the weaker members of the Clearwater, the Kcw, Kca, Kcc and Kce, have slope angles of 10 to 15 degrees. The Kcb, Kcd and Kcf Members stand much steeper because they do not have weak layers of sheared bentonitic clay. The overall slope angle in these layers can be as high as 55 degrees, but these slopes can move along a weaker layer that is lower in the geologic sequence.

The complex rotational earth-slide earth-flows are either translational blocks that slide over a steep slope in the McMurray Formation, then flow, or rotational slides that break up, then flow. The length to depth ratio of these slides is typically over 4 to 1 where the length is defined as the minimum distance from the toe to tip of the slide and the depth is defined as the maximum height of the displaced mass measured perpendicular to the plane of the surface of rupture (Cruden and Varnes 1996). Rotational landslides in the Clearwater Formation are caused by the weathering of material in the scarp of the slide and seasonal increases in the water table. Retrogressive slides occur when a newly exposed scarp is weathered and weakened causing another movement which is usually triggered by groundwater.

3.5.5 Landslides in the Pleistocene sediments

The Pleistocene sediments include the Pl_2 glacio-lacustrine deposits and the Pg_1 till discussed in Section 2.2.2. The common mode of movement in the tills and lacustrine sediments is a complex retrogressive earth-slide earth-flow. The movement starts with a shallow earth slide followed by the colluvium flowing as it loses shear strength. The rupture surface extends into the crown, opposite to the direction of movement, therefore the movement is called retrogressive. The Pleistocene sediments can slide on their own or because of movements in the underlying formations. Movements involving only the Pleistocene sediments are caused by weathering and saturation of the material and are usually triggered by groundwater or drainage over the river valley rim. An example of the Pleistocene units moving on their own is Slide 13-459c. The slide is above the steep, stable banks of the Kcd Member. Slide 11-376b is an example of the Pleistocene sediments moving because of sliding in the underlying Kcf Member.

The ultimate slope angle of the Pleistocene sediments can be estimated at 10 degrees from slope profiles measured during field investigations The angle of the Pleistocene sediments at Slide 23-806c (Chapter 6) is 11 degrees. Slide 23-806e has the same mode of movement as Slide 23-806c and is on the same stretch of riverbank. The slide site has been overgrown in the last 30 years indicating that movements in the sediments have stopped and the sediments are near their ultimate angle. The Pleistocene sediments cannot be considered at their ultimate angle because the slope does not have a terrace at the base, therefore it is not abandoned (Cruden et al. 1993). The crown of Slide 23-806c has retrogressed the same distance as the crown of Slide 23-0806e indicating that the measurement of 11 degrees is near the ultimate angle. The Pleistocene sediments generally form vertical cliffs when there is no mechanism to cause movements. The Pl_2 and Pg_1 sediments in the main scarps of translational Slides 17-617a and 10-65c are examples of the Pleistocene deposits standing at an angle of 90 degrees at heights of up to 7m. The process of retrogressive earth-slide earth flows is discussed in Chapters 6 and 7.

3.5.6 Landslides in the river terrace deposits and colluvium

Slides in terrace deposits are rare along the MacKay River. The deposits move as a composite debris-slide debris-flow. This mode of movement is discussed in Chapter 5 under Slide 22-773f.

The common mechanism for movement in the colluvium is the down-slope sliding of rafts of material held together by tree and plant roots. This process is common in most landslides from km 35 to 80 in the MacKay River valley. Rafts up to 5m in length and width and 1m in thickness are observed in some landslides. The sliding colluvium can translate up to 20m down the slope. The surfaces of rupture lie in saturated, weathered colluvium beneath the root-reinforced soil. These slides are probably triggered by periods of high rainfall.

3.5.7 Sites selected for field investigations

Six landslide sites were selected on the basis of the information obtained during the aerial reconnaissance and the terrain analysis of the MacKay River valley. The landslide sites were selected so all modes of movement would be investigated during the site visits. Figure 3.5.7 shows the locations of the six selected sites and the eight selected sites for future monitoring (Section 3.5.9). The sites are summarized in Table 3.5.7.

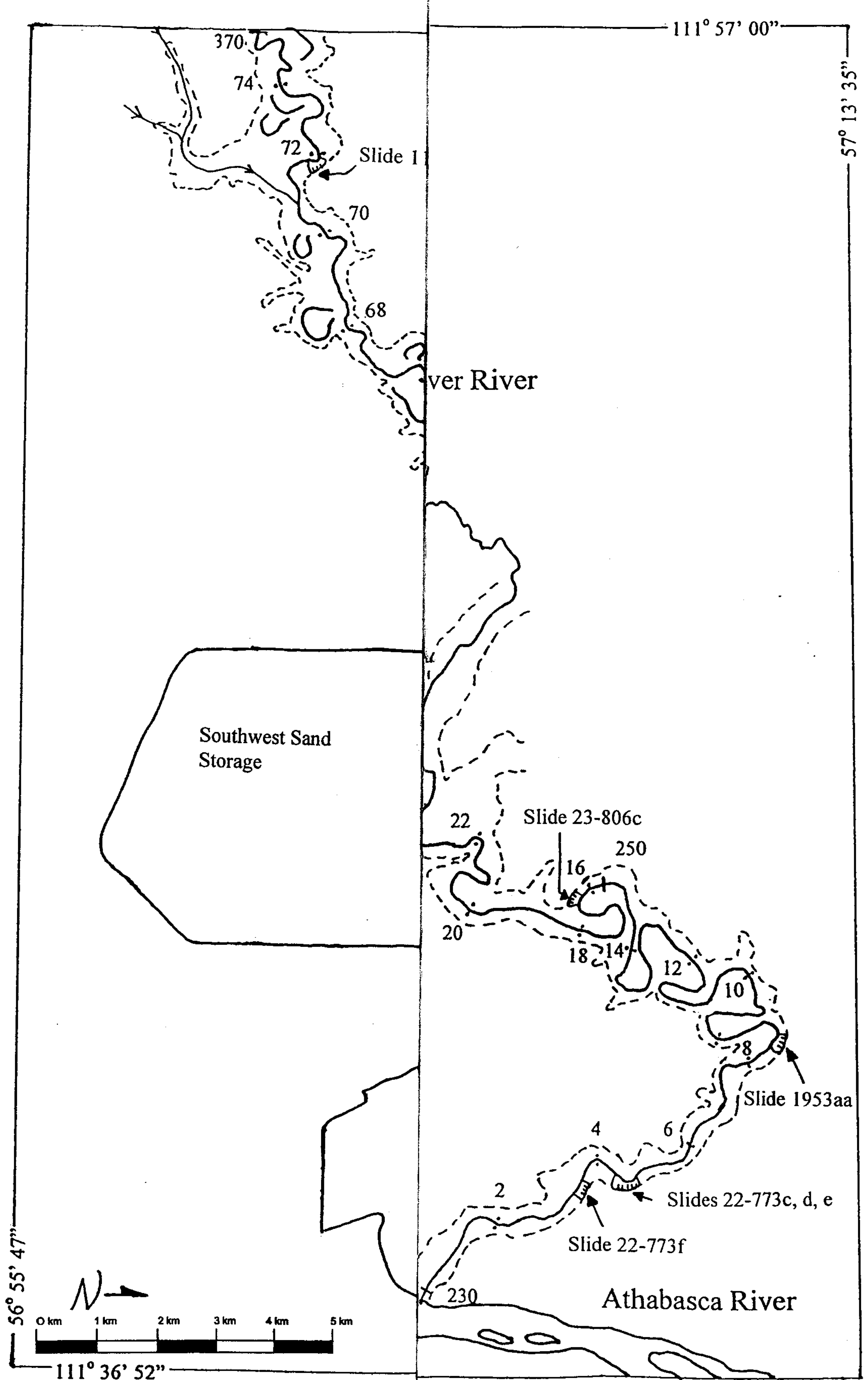

111° 57' 00"
57° 13' 35"
370
74
72
Slide 1
70
68
ver River
Southwest Sand
Storage
22
Slide 23-806c
16
250
20
18
14
12
10
8
Slide 1953aa
4
6
2
Slides 22-773c, d, e
Slide 22-773f
230
Athabasca River
56° 55' 47"
N
0 km
1 km
2 km
3 km
4 km
5 km
111° 36' 52"

Table 3.5.7. Landslide sites selected for field investigations

Landslide name	Location	Mode of movement
11-376b	km 72	Retrogressive shallow earth-slide earth-flow
11-65c	km 39	Translational earth slide
17-617a	km 38	Translational earth slide
23-806c	km 16	Retrogressive rotational earth-slide earth-flow
1963aa	km 8	Complex rock topples and rock slides
22-773f	km 4	Composite debris-slide debris-flow

These six landslides will be discussed in the next four chapters, that are ordered from the simplest to most complex modes of movement.

Slide 11-376b is located 800 m upstream of the MacKay River bridge on the AOSTRA Road. The primary reason for selecting this site was its accessibility. The landslide appears to have rupture surfaces no deeper than 5m in the Clearwater Formation.

Slides 17-617a and 10-65c are translational landslides. Slide 17-617a was selected because it was not overgrown and appeared to have a rupture surface at least 30m below the rim of the river valley. Slide 10-65c was selected because the surface of rupture appeared to be higher in the geologic cross-section than Slide 17-617a.

Slide 23-806c is a composite earth slide-earth flow in the Clearwater Formation. It was selected because it is not overgrown and it has a zone of accumulation (Cruden and Varnes 1996) protruding into the river channel.

Slides 1953aa and 22-773f are in the McMurray Formation. Slide 1953aa was selected because it was accessible by foot and had the typical shape of the complex rock topple and rock slide. Slide 22-773f was selected because of the zone of accumulation at the base of the slide and it is accessible by foot. The zone of accumulation was created by a composite debris-slide debris-flow of river terrace deposits.

3.5.8 Conclusions

There are 7 modes of landsliding found in the MacKay River valley. These modes are ordered by complexity: single, composite and complex (the geological unit they occur in is noted in brackets):

1. Rock falls (Waterways)
2. Translational earth slides (Clearwater)
3. Earth and debris flows (colluvium)
4. Composite debris-slide debris-flows (colluvium and river terrace deposits)
5. Complex rock topples and rock slides (McMurray)
6. Complex retrogressive rotational earth-slide earth-flows (Pleistocene and Clearwater)
7. Complex retrogressive shallow earth-slide earth-flows (Pleistocene, Clearwater and basal clays)

Important observations include:

- The slopes above every river bend should be considered either active or dormant,
- 10 percent of the total length of the valley rim has active or dormant landslides,
- There have been two movements over $5x10^4m^3$ in the Clearwater Formation since 1953,
- There is no evidence of deep-seated movements in the McMurray Formation and
- There is no evidence of large landslides displacing over $1x10^6m^3$ of material in the river valley.

3.5.9 Recommendations for monitoring sites

I recommend that seven landslide sites be monitored over the life of the Syncrude mine site to provide more information on the rates of river bank retreat and movement modes. These sites are ordered sequentially in a downstream direction in Table 3.5.9. Figure 3.5.7 shows the locations of these landslides.

These eight slides cover all the modes of movement discussed in the chapter except for rock falls and composite debris-slide debris-flows. These two modes of movement involve very small volumes of material when compared to the other 5 modes of movement, therefore are not considered a priority for monitoring. All the landslide sites listed in Table 3.7.1 have earth and debris flows in the colluvium except for Slides 1953aa and 22-773c, d, and e.

The slides discussed in detail in Chapters 4 to 7 will not be discussed in this section. Slide 11-382b is a translational earth slide. The site is on the outside of a tight bend in the river were erosion rates are high. The crown of the slide is approximately 35m above the river and the crest is 145m wide. Movement is along the Kce Member of the Clearwater Formation and is caused by the erosion of the slope toe by the MacKay River.

Table 3.5.9 Sites recommended for monitoring.

Slide number	Crest width (m)	Activity	Mode of movement	Discussed in	Road access
11-376b	210	Active	Complex retrogressive shallow earth-slide earth-flow	Chapter 7	Yes
11-382b	145	Active	Translational earth slide	No	No
13-459a	375	Active	Complex retrogressive earth-slide earth-flows	No	No
17-617a	225	Dormant	Translational earth slide	Chapter 4	No
18-656g	80	Dormant	Translational earth slide	No	No
23-806c	90	Active	Complex retrogressive earth-slide earth-flows	Chapter 6	No
1953aa	50	Active	Complex rock topples and rock slides	Chapter 5	Yes
22-773c,d,e	445	Active	Complex rock topples and rock slides and complex shallow earth-slides earth- flows at base.	Chapter 5	Yes

Slide 14-459a is a complex retrogressive earth slide-earth flow that is caused by toe erosion and a beaver pond 70m behind the crown of the slide. The site is on the outside of a tight bend in the river. The crest is 375m wide, but approximately 200m of that is active and the crown of the slide is approximately 40m above river level. The area's original drainage was through a small creek in a large gully that runs to the west. Drainage has been re-routed over the crown of the landslide by beaver dams.

Slide 18-656g is a translational landslide that started to move between 1975 and 1991. The site is on an abandoned river bank and is dormant. The slide is 25m high and 80m wide. The movement is along the Kca Member of the Clearwater Formation and is caused by drainage over the main scarp of the landslide. The slide has a small 7m high main scarp and has a horst split by a rotational movement in front. I would expect this slide to continue moving until its profile resembles that of Slide 17-617a with a main scarp approximately 15m high.

The first stage of the monitoring process is the placement of air photograph targets at each site. These targets should be placed behind the crown, behind any minor scarps, at the toe and on any accumulations (if the slide is a translational earth slide). A yearly 1:10 000 air photograph analysis will determine if there have been significant movements at each of the sites. It is recommended that each site be surveyed with a Global Positioning System accurate to plus or minus 1m in the co-ordinate location and the elevation. The sites can be surveyed when the air photograph targets are being placed.. Sites that are accessible by road can be surveyed at regular intervals and sites accessible by canoe or helicopter can be surveyed whenever there is an opportunity. Sites should be re-surveyed if any movements are discovered during the yearly terrain analysis.

Slide 1953aa is not covered by the current flight lines over Syncrude Lease 22. This site could be visited semi-annually to check for any significant movements or the flightlines could be extended to the north

Chapter 4 Landslides 17-617a and 10-65c

4.1 Introduction

The next four chapters describe landslide sites visited during the summer of 1995. The chapters are ordered from the simplest to the most complex style of movement as described by Cruden and Varnes (1996). The chapters are ordered as follows:

1. Chapter 4: Landslides 17-617a and 10-65c (translational earth slides),
2. Chapter 5: Landslides 1953aa, 22-773f and 22-773c, d and e (complex rock topples and rock slides),
3. Chapter 6: Landslide 23-806c (complex retrogressive rotational earth-slide earth-flow) and
4. Chapter 7: Landslide 11-376b (Complex shallow retrogressive earth-slide earth-flow).

The first part of each chapter is a discussion of the individual landslides. These discussions are divided into an air photograph interpretation section and a field investigations section. The field investigations section includes the field observations, the groundwater conditions, soil sampling and the slide profile. The next part of the slide investigation is a literature review and a slope stability analysis where applicable. The sections describing each individual slide is followed by a general discussion and finally conclusions. Slide 17-617b is located at km 38 and Slide 10-65c is located at km 39. Figure 3.1.1 shows the locations of these landslides. Currently, access to both slides is by helicopter.

The investigation of Slide 17-617b is presented first, then Slide 10-65c is discussed. There is a literature review and slope stability analysis included with Slide 17-617a. A discussion follows the sections devoted to each slide and the chapter finishes with conclusions. Figure 4.1 is a photograph of Slide 17-617b taken on May 8, 1995 from a plane flying to the west of the site

Figure 4.1. Photograph of Slide 17-617a.

4.2 Slide 17-617a

4.2.1 Air photograph interpretation

Four sets of air photographs are discussed in this section. They are summarized in Table 4.2.1. These air photographs were obtained from Alberta Photo Services (Maps Alberta) and Western Photogrammetry and are blown up to a scale of 1:6000.

Table 4.2.1 Air photographs of Slide 17-617a.

Identification number	Date	Original scale	Source
AS 547 204	1953 09 14	1:15 840	Maps Alberta
AS 964 159	1967 08 29	1:31 680	Maps Alberta
AS 1416 81	1975 07 27	1:6 000	Maps Alberta
WP-9117-17-617	1991 10 18	1:10 000	Western

Figure 3.2.1 shows the area surrounding Landslide 17-617a. There is a marsh that is setback an average of 200m from the rim of the valley in this area (*refer to* air photograph 17-617 in Appendix B). The marsh drains into the MacKay River to the south of the slide site. In 1953 the drainage was over a 100m length of valley rim, 70m south of what will become the southern flank of Slide 17-617a. Over the next 30 years, the drainage has concentrated itself over a 30m length of valley rim, 130m south of the southern flank of the slide. The vegetation behind the scarp of the landslide is poplar trees, indicating the area is dry.

The 1953 air photographs show that the bedrock and slope colluvium in the area of the slide formed an approximately 30 degree slope with a steeper scarp on what will become the south flank of the slide. At the base of the 30 degree slope is a slope dipping towards the river at approximately 8 degrees. The estimates of slope angle are based on comparisons with the steeper stable gravel slope north of the landslide site that was measured at 35 degrees during a field visit. The scarp and the front slope form a point of land that extends 30m beyond the rest of the valley rim in the area. Figure 4.2.1a shows an overlay on the 1953 photograph (AS 547 203) and a sketch profile of the slide.

The vegetation at the base of the 30 degree slope and adjacent to the sides of the point of land is less dense than the surrounding vegetation. Colluvium had flowed from the scarps beside the north and south flank of the future slide. The 1953 air photographs show that the vegetation is in the process of recovering and the flows occurred several years before 1953.

The point of land forming what will become Slide 17-617a is surrounded by landslide deposits. The following observations support this statement:

1. The river channel is very narrow in the bend of river in front and upstream of Slide 17-617a in all air photographs interpreted for this chapter. The width of the channel has remained nearly constant over the last 40 years, indicating that the movements that caused the narrowing of the river occurred prior to 1953. Figure 4.2.1a shows the narrow reach of river channel.

2. The valley walls upstream of the slide site are shallower than 30 degrees and the land surface at the base of the 20 degree upstream slopes is higher than the areas in front of Slide 17-617a. This variation in topography is likely caused by material moving off the upstream slopes depositing colluvium at the bases of the slopes,

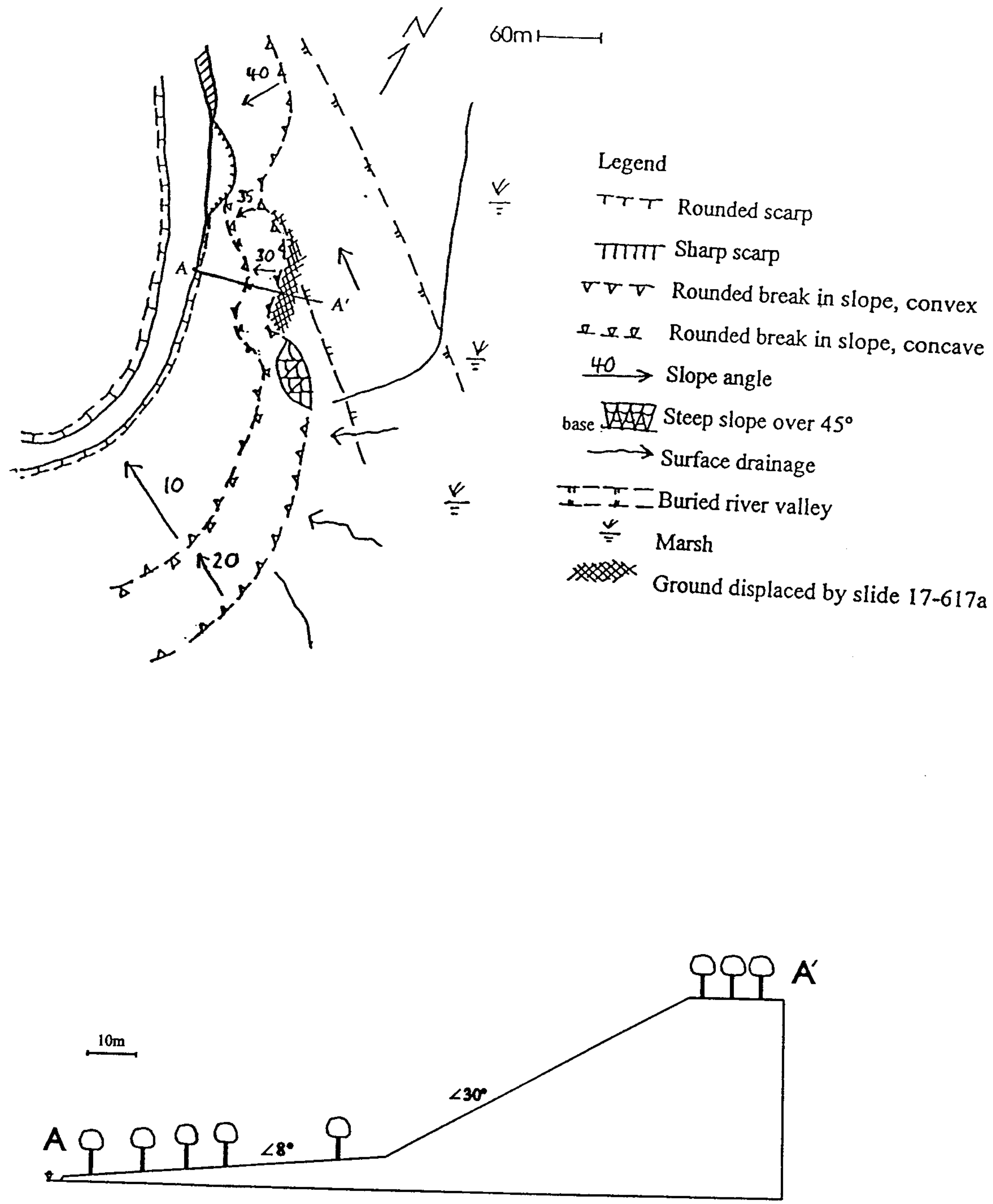


Figure 4.2.1a. Overlay of air photograph AS 547 204 and profile of Slide 17-617a in 1953.

3. The steep scarps on the south flank and upstream of Slide 17-617a could not be formed by downcutting of the river because no fluvial sediments have been deposited at the bases of these slopes. On the 1953 air photographs the angles of these scarps are approximately equal to the angle of the main scarp formed by Slide 17-617a and

4. The flows that deposited material on the shallow slope to the sides and the front of Slide 17-617a are probably movements of colluvium deposited in earlier translational landslides.

The 1:32 000 scale air photographs of unknown origin from 1958 (discussed in Section 3.4) show that no translational movements have taken place, but there are some shallow movements on the south scarp of the point and the upstream scarps of the river valley . The movements are identified by the colluvium deposits and loss of vegetation at the base of the scarps.

On the 1967 air photographs, the main scarp of the landslide is visible, but still shallow. The main scarp is about 5m high and extends into the sand of Channel 2 beside the north flank of what will become the main block of material in the slide. The graben has started to form because the antithetic minor scarp (Cruden et al. 1991) casts a shadow. A block of earth 10m by 10m has started to rotate on the north flank of the area in the slide that will become the accumulation. Between 1958 and 1967 there was little effect on the vegetation on the slide because the displacements in the main body of slide were relatively small. The only loss of vegetation was in areas adjacent to the main scarp. Figure 4.2.1b shows an overlay of the 1967 photograph (AS 964 159) and a sketch profile of the slide.

On the 1975 air photographs the graben has become more obvious and a tension crack had appeared in the middle of the graben. The main scarp and the antithetic minor scarp are very visible because the graben had dropped approximately 5m since 1967. The block of earth rotating off the north flank of the main slide had clearly moved down and

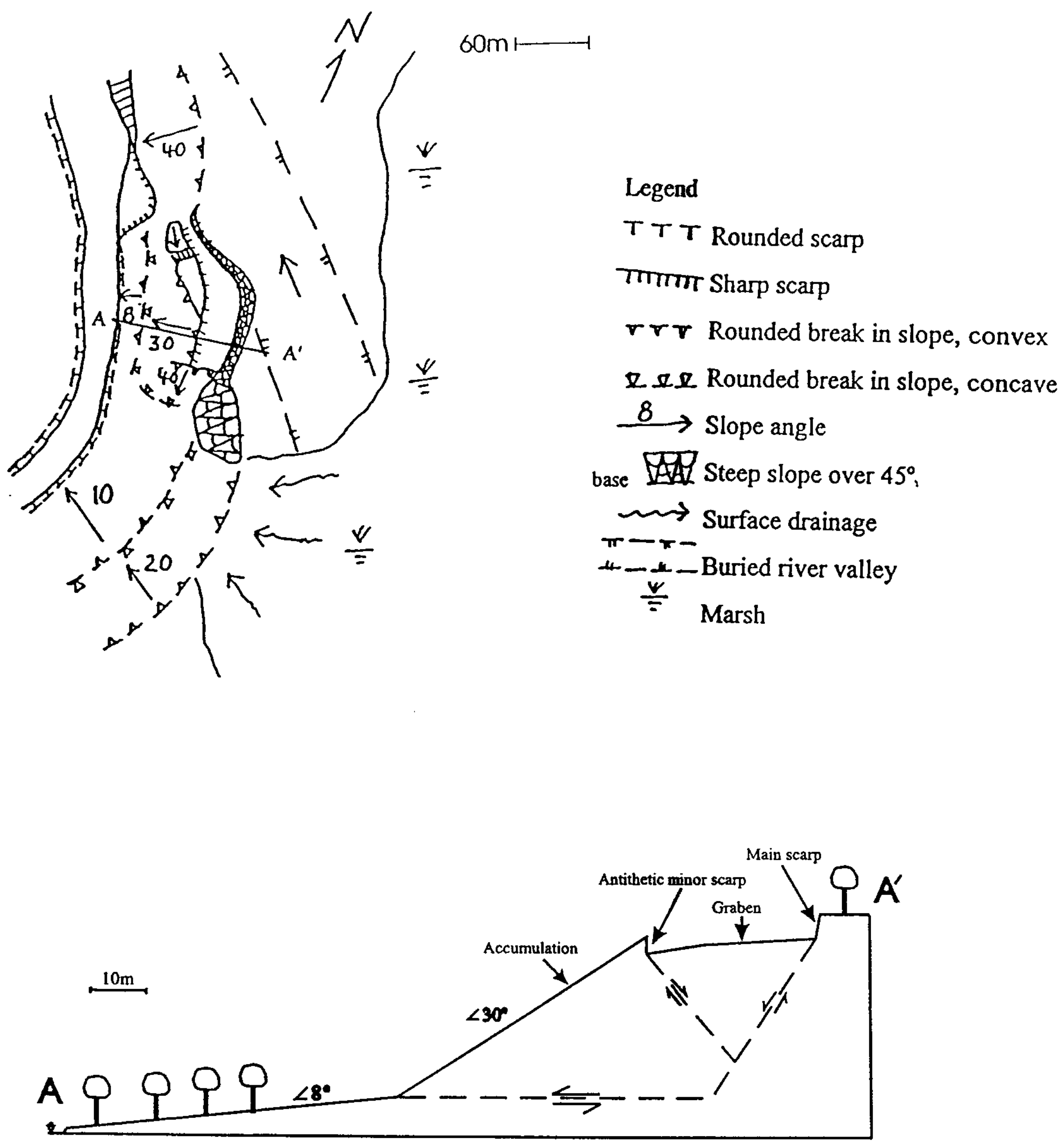


Figure 4.2.1b. Overlay of air photograph AS 964 159 and profile of Slide 17-617a in 1967.

out. A larger block of material that is approximately a 12m section of the front of the accumulation has started to rotate. A smaller rotational slide is developed at the toe of this rotational slide. Another rotational slide has developed in the sand adjacent to the north flank of the main slide when the crack that extended into the sand filled with water. The sand has flowed after it rotated and formed a zone of accumulation that extends approximately 70m, 10m into the river that is 60m from the base of the original slope. The sand in the main scarp of the slide stands at 45 degrees. In 1975, most of the vegetation had been lost around the south flank, north flank, and northwestern portion of the area in front of the accumulation because of small earth-flows moving off the larger rotational slides. The vegetation beside the northern flank has been killed by a sand flow that created the zone of accumulation that extended into the MacKay River. Figure 4.2.1c shows an overlay of the 1975 photograph (AS 1416 81) and a sketch profile of the slide.

The 1991 air photographs show the surface of the graben has dropped since 1975. There is a large shadow on the graben cast by the minor scarp between the accumulation and graben. The tension crack in the center of the graben does not appear to have widened or have any displacements along it since the 1975 air photograph. The minor scarp between the accumulation and the larger rotational slide off the front is now twice the height. The block of earth that rotated off the front has started to flow and spread out increasing the size of the zone of accumulation at the toe of the slide. The smaller rotational slides that moved off the body of the main rotational slide and the block that rotated off the south flank of the accumulation have had earth slides earth-flows off the front, leaving knife-edged ridges. By 1991, the vegetation had re-grown in the areas around the northern and southern flanks of the slide. The vegetation in front of the accumulation has started to re-grow, but it is less dense than the vegetation beside the flanks. Figure 4.2.1d shows the overlay of the 1991 photograph (WP 9117-17-617) and a sketch profile of the slide.

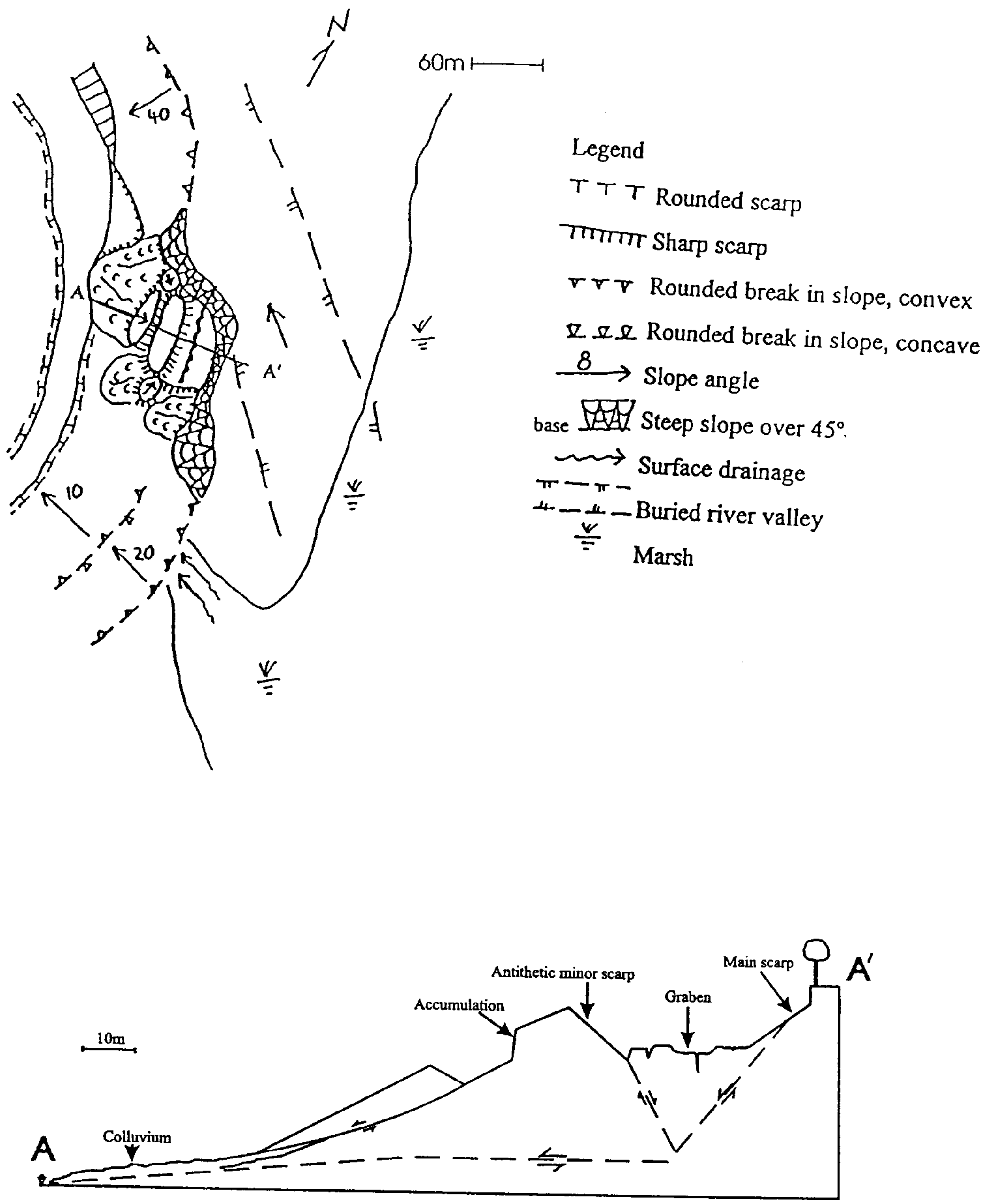


Figure 4.2.1c. Overlay of air photograph AS 1416 81 and profile of Slide 17-617a in 1975.

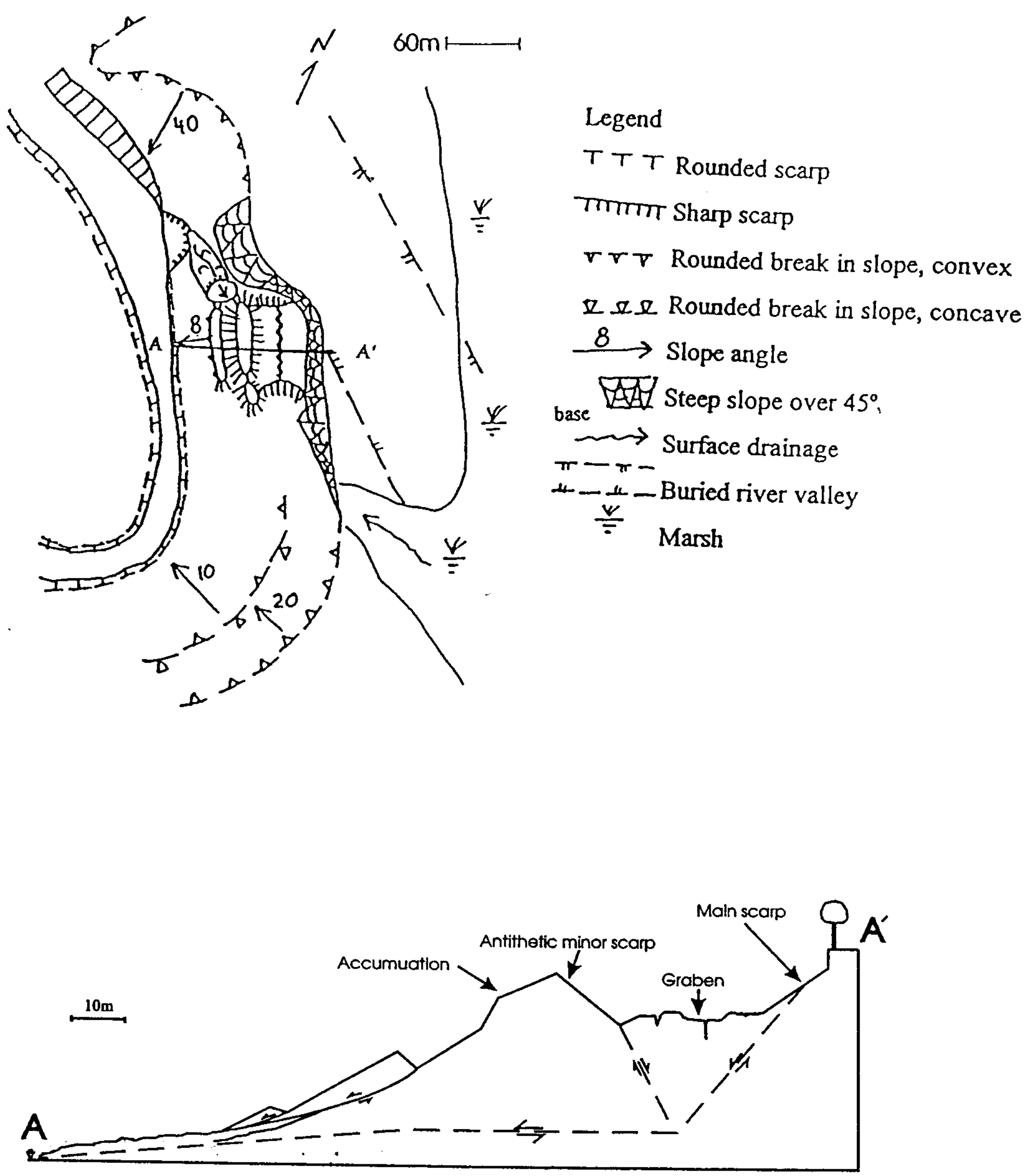


Figure 4.2.1d. Overlay of air photograph WP 9117-17-617 and profile of Slide 17-617a in 1991.

4.2.2. Field Investigations

Field observations

The field investigations revealed that since 1991 the only movement has been the rotation of approximately half the accumulation block. The block is much larger on the south flank than on the north flank and has rotated to the southwest rather than to the west (the direction of movement of the earlier rotational slides). The main scarp of the rotational slide is 4m high through the centre profile of the main slide.

There is colluvium overlying the Kcw and Kcb Members in the northern and centre portions of the accumulation. The colluvium generally slopes toward the northeast indicating that it is possibly the remnants of the old valley slope of Channel 2. Rotational sliding off the front and north flank of the accumulation are probably a result of the colluvium being weaker than the intact Clearwater Formation soil around it. The colluvium has the same glacial sediments overlying it as the Kcc Member in the main scarp of the slide. The contacts between the colluvium and the glacial sediments and the Kcc and the glacial sediments in the front and back of the accumulation are level. The bedding is also level in outcrops along the northern flank of the graben indicating that the movement is translational and there has been no rotation of the graben or accumulation block.

The soil below the toe of the slide has many tension cracks parallel to the direction of the river and perpendicular to the direction of movement of the slide. The soil appears to be colluvium derived from the Clearwater Formation and is soft. This is probably a result of weathering. Slabs of indurated siltstone are accumulating on the shoreline of the river armouring the banks. These slabs could come from the same layer in the Clearwater Formation that is near river level or be debris.

The buried Channel 2 (Section 3.2.2) outcrops along the scarp to the north of the main scarp of Slide 17-617a. Structural data discussed in Section 3.2.2 show that the channel runs behind the main scarp of the landslide. The exact position of the channel after it disappears from outcrop is unknown because there are no boreholes intercepting the channel in the area and the channel cannot be found on the air photographs because of the blanket of glacio-lacustrine deposits covering the area.

Groundwater conditions

There are no signs of springs or seepage from the deposits of the buried river channel along the exposed outcrops along the main scarp of the slide and along the cliffs to the north of the slide. It is possible that seepage in the channel is at the river level because the bottom of the channel is not visible in outcrops along the river to the north of the landslide site. The colluvium at the base of the main scarp and the soil in the upper portions of the accumulation are also dry. Field investigations were conducted on 2 days that followed 7 and 4 days of continuous rain, therefore site visits were excellent opportunities to find sources of seepage. Surface runoff is drained by rills no deeper than a few centimetres along the outcrops of Channel 2. No flow of water was noted over the crown of the landslide at any time or in any location.

The only areas of the slide that are wet are the bottom half of the colluvium in the most recent rotational slide and the material in the toe and below the toe of the slide. There is actually a small pond approximately 50m^2 in area and 1m deep skirting the northeastern toe of the landslide.

Thomson and Morgenstern (1977, p.521) stated that "preglacial valleys, for the most part, are floored with clean, free-draining, thick deposits of early Pleistocene sands and gravels. These valleys are also about as deep as present post-glacial valleys. When the preglacial valleys intersect modern valleys, the water table in their immediate vicinity is lowered by the subterranean drains afforded by the Pleistocene sands and gravel. The stabilizing effect is dramatic and is clearly evident …". The description of the preglacial valleys in the study by Thomson and Morgenstern (1977) is similar to that of Channel 2 deposits except that Channel 2 is in-filled with sand rather than glacial till. The Channel 2 deposits have permeabilities of at least two orders of magnitude higher than surrounding clay-shale units which will act as a drain behind the main scarp. The effect Channel 2 has in reducing the water table and increasing the stability of the immediate area is countered by the effects of weakened earth on the sides of the buried channel. The weathered colluvium is in the north flank and at an unknown distance behind the main scarp of Slide 17-617a. The soil in the main scarp of the slide is Kcc bedrock and the contact between the channel deposits and the Kcc north of the main scarp does not contain colluvium.

Slide profiles

Figure 4.2.2a is a profile of Slide 17-617a. The profile is through the centre of the displaced material and is measured with a 50m tape and an inclinometer. The original profile of the slide was estimated with the 1953 air photograph that shows an approximately 30 degree slope with a shallow slope at the base of the main block of material displaced by the slide. The profile is constructed so that the cross-sectional area of the current profile has a 10 percent increase in the volume over the cross section of the in situ material.

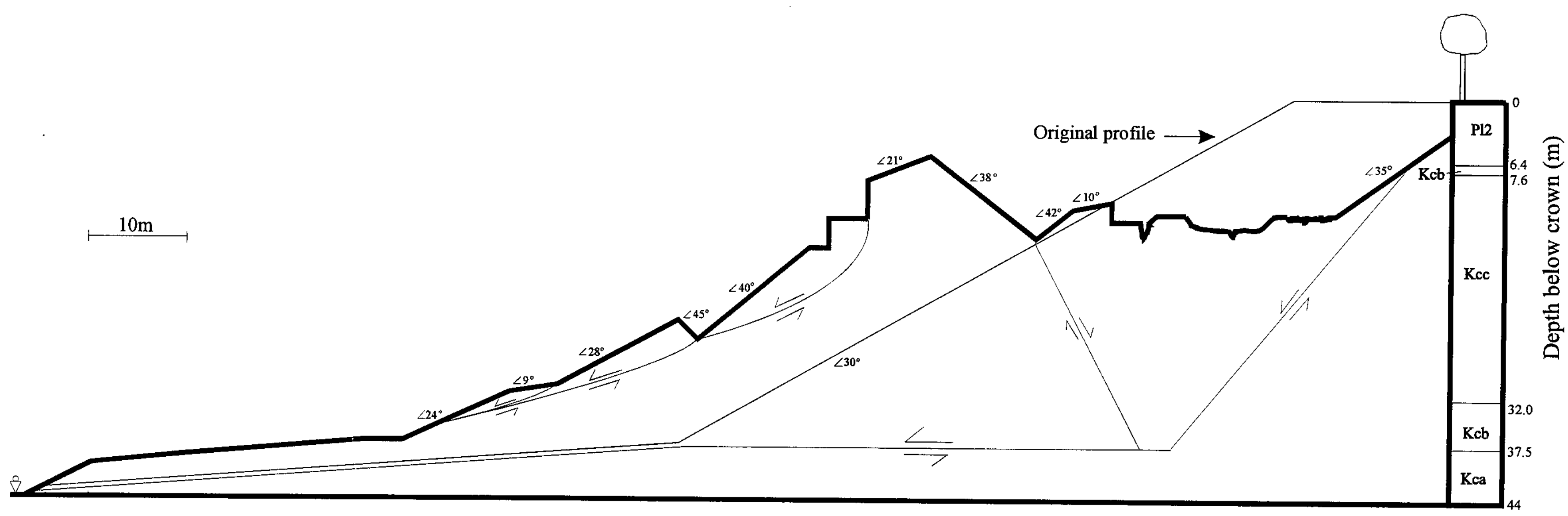


Figure 4.2.2a. Cross section through centre of Slide 17-617a.

The geologic profile of the slide is obtained from Syncrude borehole 39-54-00. The elevation of the river at the base of slide is 289m and the height from the river to the crown of the slide is 43m, therefore the elevation of the crown of the slide is 332m. I consider the elevation of the borehole (331.2m) and the crown of the slide equal (332m), therefore the borehole log is representative of the geologic cross section of the landslide although the hole is 270m to the east of the landslide crown. The borehole log also has the same thickness of glacial sediments as the main scarp of the landslide and the elevation of the McMurray Formation is identical to the elevation of outcrops in an area 200m upstream from the slide. Lobb and McMullin (1989, p.105) stated that "the thicknesses of each subunit (Clearwater member) are quite uniform throughout both Leases 17 and 22, as well as off-lease to the south and west".

I estimate that the rupture surface is 35m below the crown of the landslide from the geometry of the landslide and extends into the colluvium at the front of the landslide. The borehole data suggest that the movement has occurred in a weak layer in the Kca Member. This estimate is supported by the following information:

1. There are no sheared layers in the Kcw (Klohn Leonoff 1990),
2. There is one sheared layer in the Kca that has lower residual strengths than the sheared layers in the overlying Kcb and
3. The soil that outcrops at river level was identified as Kcw from the description in Lobb and McMullin (1989).

The following slide dimensions are measured from the profile. Cruden and Varnes (1996) described the procedure for measuring these dimensions.

- Volume of the landslide (including a 10 percent swell factor): $1.4 \times 10^5 m^3$.
- Width of main scarp: 95m
- Height of exposed main scarp: 14m
- L_r, maximum length of rupture surface: 95m
- L_d, length of displaced material: 95m
- L, total length: 108m
- W_r, width of rupture surface: 95m
- W_d, width of displaced material: 145m
- D_r, maximum depth to surface of rupture: 35m
- D_d, maximum depth of displaced material: 28m

The rim of the valley has retreated approximately 22m since the start of movements in Slide 17-617a. The earth in the accumulation has translated 22m from its original position in the valley slope. Larger displacements of approximately 50m have occurred in the toe because of the rotational slides that flowed in the toe area (refer to Section 4.2.1). Table 4.2.2 is the calculated average rates of horizontal movement for Slide 17-617a for the periods of time between successive air photographs. The average velocities are calculated from measurements of the distance between the top of the main scarp and the top of the antithetic minor scarp scaled from the air photographs and from the dimensions of the original and current profile. I believe that the landslide started to move in 1960 based on precipitation data for the Fort McMurray Airport (Environment Canada 1994) plotted in Figure 4.2.2b. There is a gradual increase in cumulative annual precipitation for each year from 1958 to 1960 with the peak rainfall in that period occurring in July 1960.

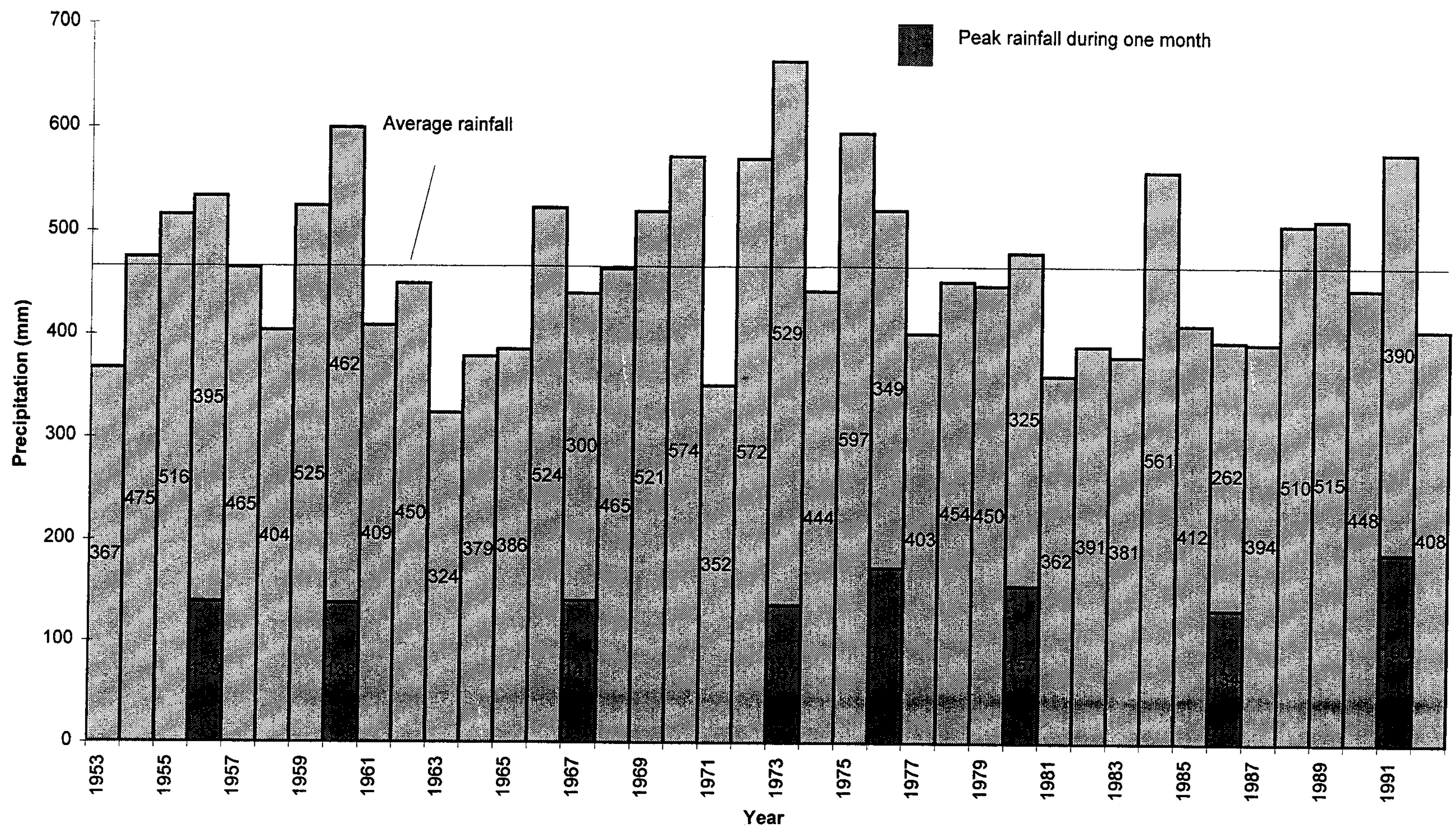


Figure 4.2.2b. Precipitation data for the Fort McMurray Airport (Environment Canada 1994).

Table 4.2.2. Average velocities of landslide 17-617a.

Time span	Displacement of crown of antithetic minor scarp	Average velocity
July 1960 to July 1995	22m	0.6m/yr
July 1960 to Aug. 1967	8m	1.1m/yr
Aug. 1967 to July.1975	7m	0.9m/yr
July 1975 to Oct. 1991	3m	0.2m/yr
Oct. 1991 to July 1995	4m	1.0m/yr

Cruden and Varnes (1996) classified the rates of movement of landslides into 7 velocity classes. The overall average rate of movement of 0.6m/yr fits is in the range of very slow landslide velocities. Peak velocities may be much larger because the movements may be triggered by rainfall and occur over a few hours or days. Actual velocities during similar movements may range from moderate to rapid (13m/month to 3m/min.) (Thomson and Tweedie 1978, Kim 1992 and Cruden et al. 1995). Cruden et al. (1995, p.1000) stressed the "transition of movements from rapid translational slides common in the soft Cretaceous bedrock to slow earth flows."

4.2.3 Literature review

Thomson and Tweedie (1978) Kim (1992) and Cruden et al. (1995) conducted research on the Edgerton Landslides. The slides are in a Late Cretaceous age clay-shale formation with sheared clay layers and are divided into north, south and east movements. It is useful to compare the rates of displacement because both the Edgerton slides and Slide 17-617a are translational landslides in a clay-shale formation moving along a layer of sheared bentonitic clay at residual strength, although the triggers for the movement are different. The Edgerton landslides are reactivated landslides and are not caused by toe erosion because the toes of the slides appear midway up the valley.

I estimate that the north slide translated at a rate of 5 to 10m/day during the first two days of movement based on the description of the slide provided by Thomson and Tweedie (1978). Kim (1992) concluded that the average rate of movement of the north slide was 1m/yr from 1974 to 1991, showing that the slide velocity has decreased with time. The average velocity for Slide 17-617a is comparable to the average velocity of the Edgerton landslides.

In a summary of translational landslides in the Cretaceous deposits of North America for the last 100 years, Brooker and Peck (1993, p.527) stated "the rate of movement of active slides is about 100mm/yr" from observations of nine case records. The cause of movements for the nine slides include: excavations, progressive failure, toe erosion and building on active sites. Observed rates of movement were within the range of 97 to 105mm/yr for the five examples cited (Brooker and Peck 1993, p.543) with the exception of the long term rate of movement of 60-90mm/yr over a period of 10 000 years for the Savery Creek slide. All slides have about the same rate of movement regardless of the cause of movement, the volume of material displaced and the location of the slide site. The average rate of movement of Slide 17-617a is 6 times the average rate of movement, 100mm/yr.

Geotechnical properties

Table 4.3.4a is a summary of the geotechnical parameters of the Clearwater Formation compiled by Klohn Leonoff Limited (1990) for their geotechnical design report for the Southwest Sand Storage Facility. Klohn Leonoff (1990, p. I-31) stated that the values of residual strengths "for critical Clearwater Formation units have been successively reduced based on observed performance and additional investigations".

Table 4.2.3a. Geotechnical properties of the Clearwater Formation and the Pleistocene deposits (Klohn Leonoff 1990).

Clearwater Member or Pleistocene deposit	Cross bedding angle of friction (∅′)	Residual angle of friction ($∅'_r$)	Cohesion (c′) (kPa)	Unit weight (kN/m^3)
Lacustrine	24	24	0	21
Till	32	32	0	21
Kcf	17	6	0	21.5
Kce	17	6	0	21.5
Kcd	17	10	0	21.5
Kcc	17	6	0	21.5
Kcb	17	6	0	21.5
Kca	17	6	0	21.5
Kcw	17	12	0	21.5

Note: The angles of friction (∅′and $∅'_r$) for the till and lacustrine deposits are angles of friction perpendicular and parallel to bedding in the Clearwater Formation. The Pleistocene deposits do not contain sheared layers and the till is not stratified.

The lowest $∅'_r$ in Table 4.3.2a is 6 degrees, but some laboratory tests have found values of 4.5 degrees (Klohn Leonoff 1990). This low value is not used in any analysis in this thesis, but should be noted. The strength of the Kcw and Kcd Member is higher than the other members because they have a lower average plasticity and a lower average clay content (Klohn Leonoff 1990). I believe that the cohesive strengths of the glacio-lacustrine and till deposits are conservative. The glaciolacustrine sediments can stand in vertical scarps up to 4m high and appear to have an ultimate angle of approximately 10 degrees, therefore I believe that a c′ of 80kPa and a $\varnothing'_r$ of 20 degrees are reasonable. The glacio-lacustrine deposits do have cohesion. The till possibly has a c′ of 100kPa, $\varnothing'$ of 32 degrees and a $\varnothing'_r$ of 20 degrees near the MacKay River valley.

Isaac and Dusseault (1984) stated that the non-cemented strata in the Clearwater Formation are highly overconsolidated with liquidity indices of -0.03 to -0.27 (averages for all members) and the mean activities of plastic soils range from 0.78 to 2.02 with a mean activity of 1.33. Table 4.2.4b shows the strength parameters for soils found in the Clearwater Formation reported by Isaac and Dusseault (1984) from triaxial testing. The unconfined compressive strength of the siltstone layers ranged from 38 to 66 MPa (Isaac and Dusseault 1984).

Table 4.2.4b. Triaxial test results on Clearwater Formation samples (Isaac and Dusseault 1984).

Soil type within Formation	Peak strength ($\varnothing_p'$)	Residual strength ($\varnothing'_r$)	Peak cohesion (c′) (kPa)
Sandy silt	24° to 45°	15° to 36°	0 to 46
Clayey silt	16° to 47°	8° to 31°	0 to 122
Silty clay	14° to 27°	4.5° to 14°	0 to 91
Smectitic clay	14.5° to 31.5°	8° to 21°	14 to 230

4.2.4 Stability Analysis

The stability analysis is performed with SLOPE/W software (GEO-SLOPE 1993) using the Morgenstern-Price limit-equilibrium method with a specified slip surface and piezometric lines to indicate the water table. The mechanics of a first-time slide "are complex and do not lend themselves to reliable prediction from numerical analysis", therefore "where the ground has moved or is presently moving, analysis is much easier" (Brooker and Peck 1993, p.527). The present active landslide profile is first analyzed, then the original slope profile is analyzed. The profiles are taken from Figure 4.2.2a.

Figure 4.2.4a is the results of SLOPE-W analysis for the present day landslide profile. The following strength properties are used to obtain a factor of safety near unity:

- Clearwater Kcc, Kcb and Kca members (across bedding): $\phi' = 17^{o}$ $c' = 0$
- Sheared bentonitic Kca clay layer (horizontal): $\phi_r' = 6^{o}$ $c' = 0$
- Colluvium (estimated): $\phi' = 17^{o}$ $c' = 0$

The factor of safety of 1.03 suggests that movement may occur when the groundwater table rises 1m above the indicated value. The material properties are selected from the values given in Table 4.2.3a. The minimum residual shear strength is used in the stability analysis. It is possible that the residual shear of the bentonitic clay layer is higher (7 to 10 degrees), but there is no pore water pressure data for the back analysis. Therefore, the value of ϕ_r' of 6 degrees is used.

Figure 4.2.4b is the results of SLOPE-W analysis for the original slope profile. The following strength properties are used to obtain a factor of safety near unity:

- Till: $\phi' = 32^{o}$ $c' = 20$ kPa
- Clearwater Kcc, Kcb and Kca members: $\phi' = 30^{o}$ $c' = 65$ kPa
- Sheared bentonitic Kca clay layer: $\phi_r' = 6^{o}$ $c' = 0$

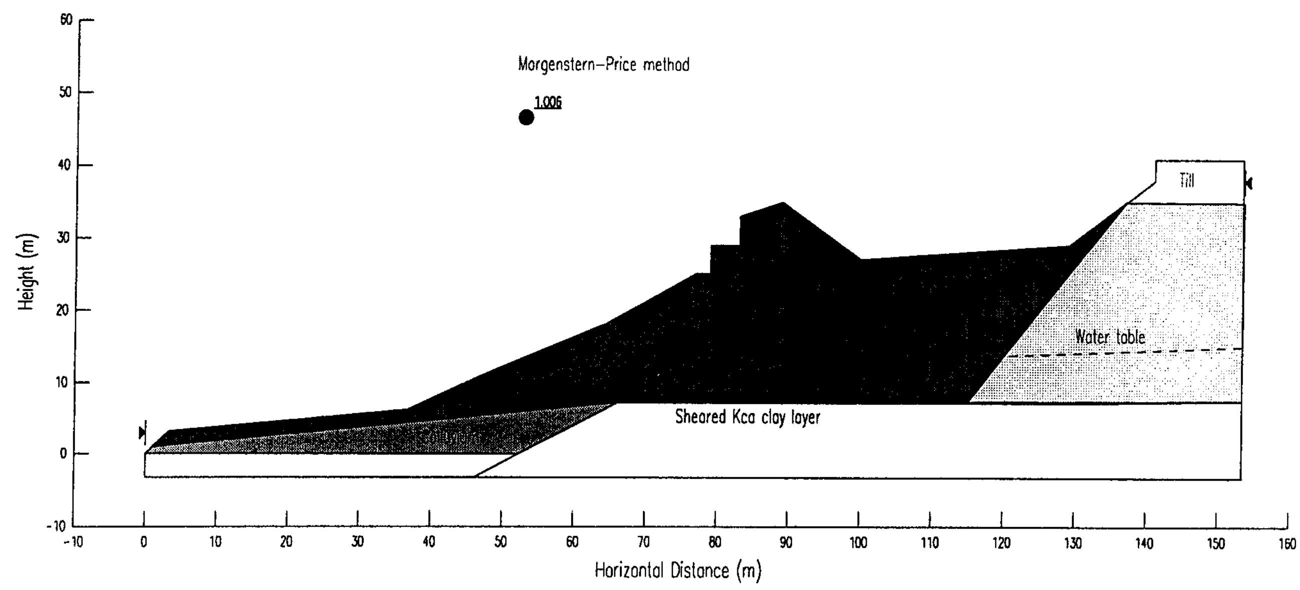


Figure 4.2.4a. Results of the SLOPE/W analysis for the present day landslide profile.

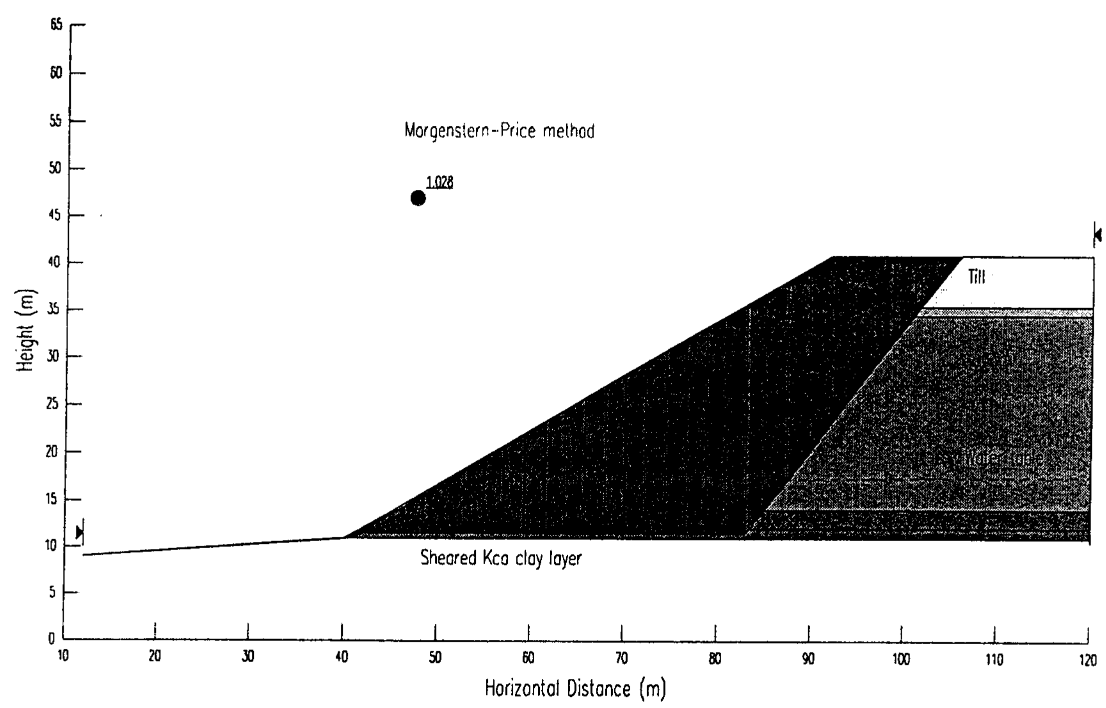


Figure 4.2.4b. Results of the SLOPE/W analysis for the original slope profile.

The factor of safety of 1.01 suggests that movement may occur when the groundwater table rises 1m above the indicated value. The shear strength of the Kca sheared layer, $\varnothing_r'= 6^o$, is identical to the value in the present day landslide profile, but the shear strength of the soil in the back scarp has been increased from $\varnothing'= 17^o$ and $c'= 0$ to $\varnothing'= 30^o$ and $c'= 65$ kPa. The higher shear strength and cohesion ($\varnothing'$ and c') in the original slope profile are within the ranges of values discussed by Isaac and Dusseault (1984) that are summarized in the previous section. There are also the 6, 20cm thick indurated layers that are logged in Syncrude borehole 39-54-00. The two highest indurated layers appear in the main scarp of the slide and are 0.5 and 1.0m thick. This is thicker than the layers in borehole 39-54-00 and is possibly explained by local variations in the thickness of the indurated layers. The indurated siltstone layers will further increase the strength of the slope by acting as reinforcement along the shear plane along the inclined portion of the surface of rupture. Joints in the siltstone would eliminate this reinforcing effect.

The slope moved after the soil softened (loss of c′) along the inclined portion of the surface of rupture. The peak shear strength ($\varnothing_p'$) of the soil was reduced to values at or near the residual ($\varnothing_r'$) during displacements. The resistance of siltstone shearing across siltstone would be lost after small displacements as the blocks move past each other and across the weaker silts and clays below them. Large displacements of over 8m in the inclined surface of rupture are sufficient to reduce the strength of the soil ($\varnothing'$) to the residual values ($\varnothing_r'$) suggested by Isaac and Dusseault (1984). The $\varnothing_r'$ values reported by Isaac and Dusseault (1984) in Table 4.2.3b should not be confused with the values in Table 4.2.3a that are for sheared flat-lying bentonitic clay layers. I believe that the cross-bedding $\varnothing'$ of 17 degrees reported by Klohn Leonoff (1989) is a minimum value used for the design of mine structures. The residual strength ($\varnothing_r'$) of the cross-bedding units is considered to average 17 degrees in the initial profile and the shear strength ($\varnothing'$) of the colluvium is also considered to be 17 degrees in the slope stability analysis of the original profile.

4.3 Slide 10-65c

4.3.1 Air photograph interpretation

Figure 4.3.1 is an overlay of air photograph WP9106-10-65. Table 4.3.1 summarizes the air photographs discussed in this section. The slide has been dormant since at least 1953. There has been no movements on Slide 10-65c with the exception of a rotational movement which occurred between 1967 and 1972 in the Kcw and Kca in the slope beneath the surface of rupture of the translational slide. The rotational earth-slide is about 50m in width and 3000m^3 in volume. I will not discuss the rotational slide in this chapter because the first movement of Slide 23-806c (Chapter 6) is similar.

Figure 4.3.1 shows that the land behind the crown of the site is dry because there is a large valley of a stream that flows into the Mackay River 2km downstream. The valley is almost as deep as the MacKay River valley. The distance between the crown of the landslide and the valley slope ranges from 50m at the upstream flank to 200m at the downstream flank. This valley is discussed in Section 3.2.2 as a possible continuation of Channel 2.

Table 4.3.1 Air photographs of Slide 10-65c.

Identification number	Date	Original scale	Source
AS 547 100	1953 09 14	1:15 840	Maps Alberta
AS 964 160	1967 08 29	1:31 680	Maps Alberta
AS 1202 118	1972 07 27	1:31 680	Maps Alberta
WP-9106-10-65	1991 05 18	1:10 000	Western

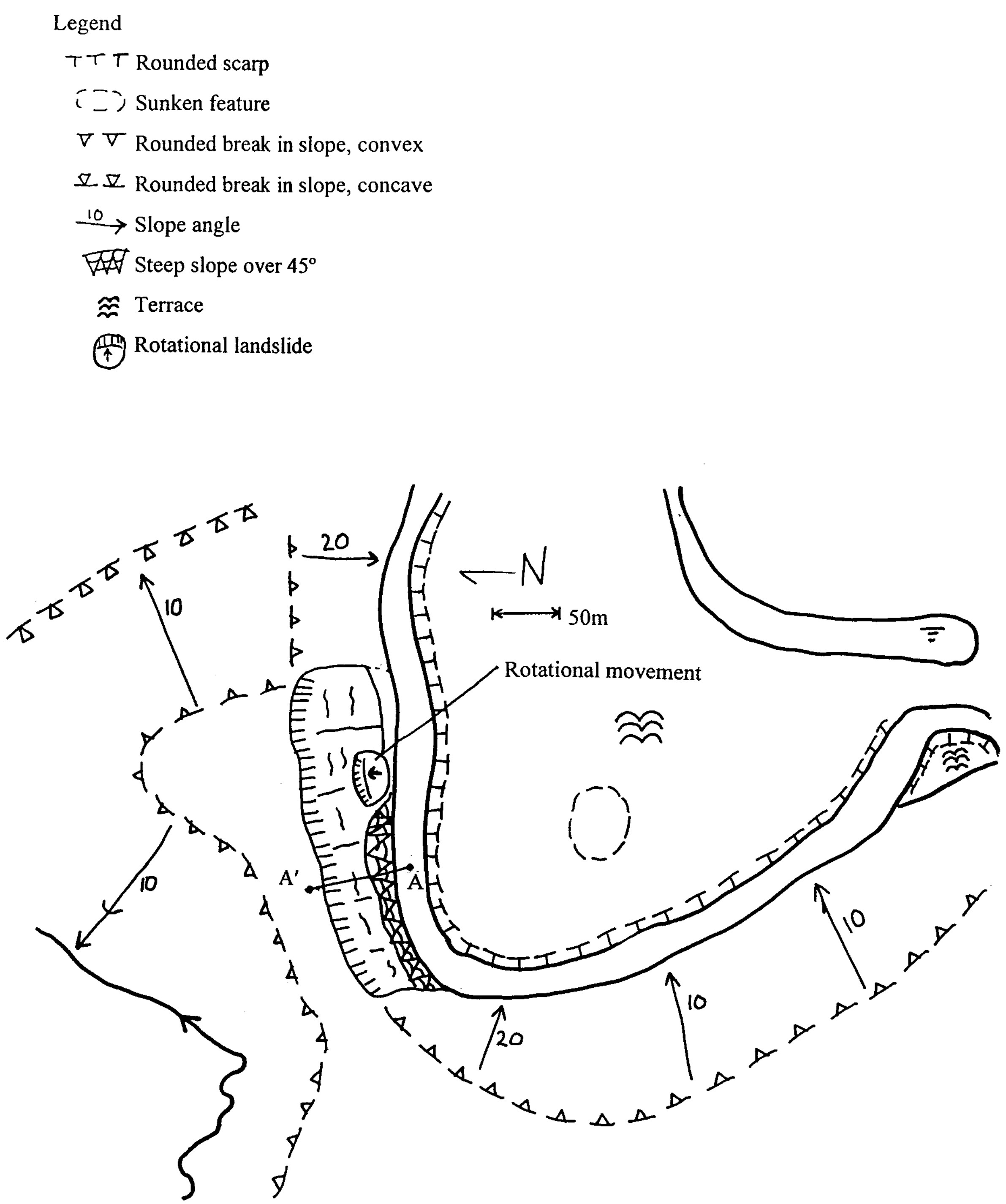


Figure 4.3.1. Overlay of air photograph WP-9106-10-65 (Alberta Photo Services). The line of the profile in Figure 4.3.2 is shown.

4.3.2 Field investigations

Field observations

The toe of the landslide is about 12m above river level. There is a 45 degree slope in the Kcw and Kca below the toe of the slide that extends to river level. Shallow slides of blocks of root-reinforced colluvium over weathered colluvium and bedrock are common above the scarp of the steep slope, but are not found in any other locations on the landslide site. These movements are discussed in Chapter 7.

The graben and accumulation are not visible on the eastern sections of the displaced material, but are visible near the western flank of the landslide. There is a steep main scarp about 15m high with an accumulation of colluvium at the base of the slope. It is difficult to make observations about the style of the movement because the landslide site is heavily vegetated.

Groundwater conditions

The slide site is dry in the upper portions of the displaced material and the main scarp. The toe of the slide is wet with a few small ponds of water. The area around the rotational slide below the surface of rupture is very wet. Surface drainage from the upper slopes probably flows toward this area, but there was no flow of surface water found during site visits. There is probably very little seepage in the area because the groundwater table is lowered by the valley north of the slide site. Not in situ measurements of pore pressures were taken during field investigations.

Slide profiles

Figure 4.3.2 is the centre profile of Slide 10-65c. The original profile is estimated from the cross-sectional area of the displaced material. There are no air photographs of the site before movements, therefore I can only guess that original profile was a terraced slope. This is probably incorrect because there are no terrace deposits on the slope, but it

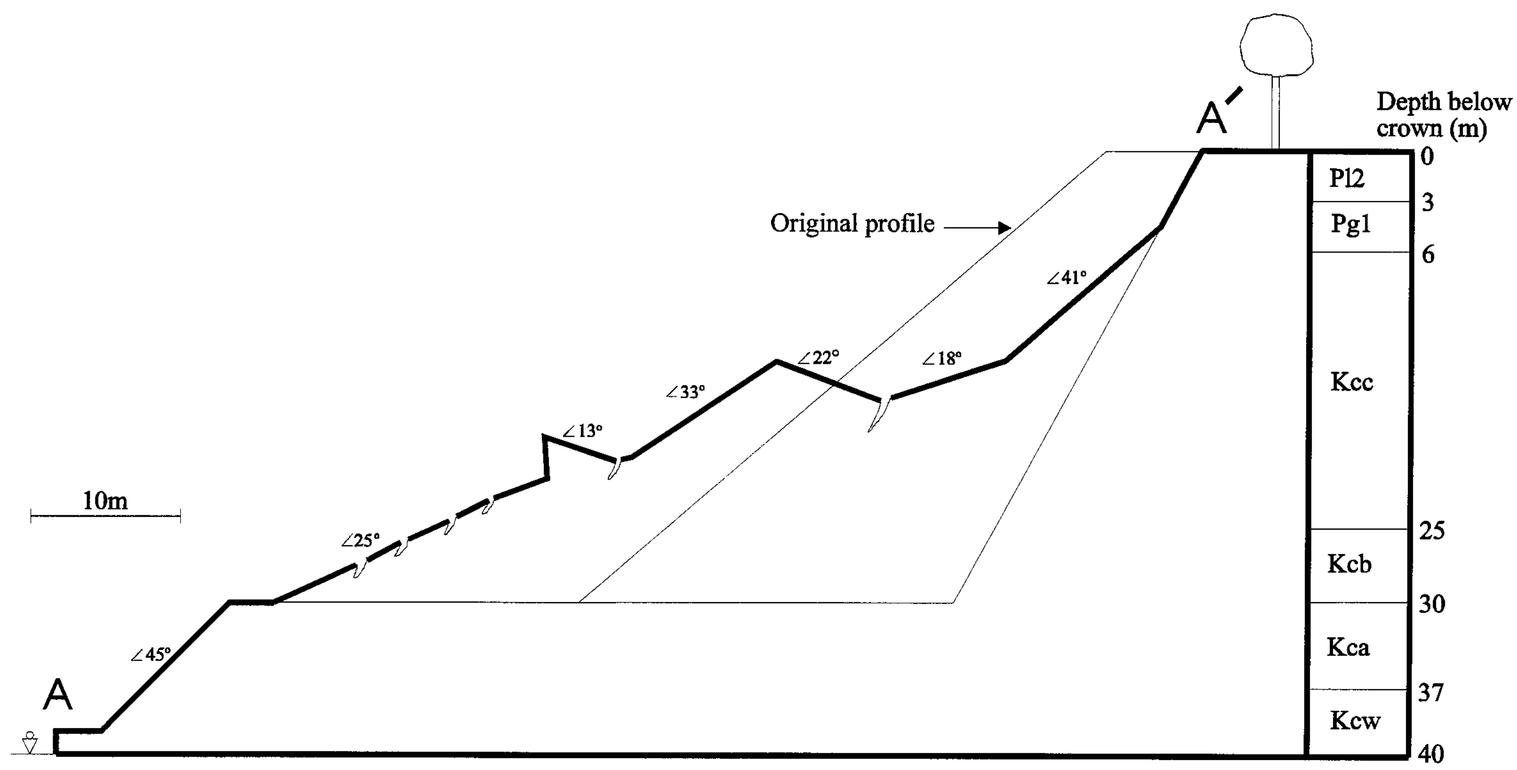


Figure 4.3.2. Centre profile of Slide 10-65c. The line of the profile is shown on Figure 4.3.1.

is otherwise impossible to construct a profile that can account for the relatively small-cross sectional area of the displaced material (*compare with* Figure 4.2.2a) The profile is constructed so that the cross-sectional area of the current profile has a 10 percent increase in the volume over the cross section of the in situ material. The following slide dimensions are measured from the current profile and estimated from the original profile. Cruden and Varnes (1996) described the procedure for measuring the dimensions.

- Volume of the landslide (including a 10 percent swell factor): $1.3 \times 10^5 m^3$.
- Width of main scarp: 300m
- Height of exposed main scarp: 10m
- L_r, maximum length of rupture surface: 60m
- L_d, length of displaced material: 60m
- L, total length: 70m
- W_r, width of rupture surface: 300m
- W_d, width of displaced material: 300m
- D_r, maximum depth to surface of rupture: 30m
- D_d, maximum depth of displaced material: 16m

The D_d of Slide 10-65c is 54 percent D_r and the D_d of Slide 17-617a is 80 percent D_r. The D_d to D_r ratio is less in Slide 10-65c possibly because it has been active longer than Slide 17-617a with greater displacements relative to the original length of its horizontal surface of rupture. The accumulation of Slide 10-65c has been weathered longer and has probably had more smaller movements of colluvium off the front than Slide 17-617a. The horizontal portion of the surface of rupture is half the length of Slide 17-617a. An explanation for the differences in geometry of the slides is that Slide 10-65c is actually a compound or rotational landslide. It is difficult to dispute this argument based on the limited information available on the site of Slide 10-65c, but a brief field visit to a Slide 18-656c (Appendix C) indicated otherwise. The slope profiles of Slides 10-65c and 18-656c are similar, but Slide 18-656c does not have an accumulation of colluvium obscuring the main scarp of the landslide. The main scarp is a steep uniform slope about 25m high. The steep uniform slope indicates that the style of movement is not rotational, but it is possible that the movement is a compound slide. Cruden and Varnes (1996, p.30) defined a compound slide as "intermediate between rotational and translational landslides" with "steep main scarps that may flatten with depth." I do not have enough information to conclude that there are compound landslides in the valley. I suggest it be investigated further to determine if there are compound movements in the MacKay River valley.

4.4 Discussion

4.4.1 Air photograph interpretation

Slide 10-65c was not originally considered a translational landslide because of the overgrowth in the area. It was originally thought to be a river terrace with a steep scarp behind it. Trees will first grow in the much moister grabens, then after a time lag of approximately 5 to 20 years on the accumulations. This time lag between tree growth allows the trees in the graben to make up the difference in elevation caused by the accumulation being higher. Air photographs of translational slides over 30 years old show that the tree tops are level in stereo vision. The landslide will appear to be a river terrace with a steep scarp behind it. As the slide becomes older, it is not necessary for the trees to start growing at different times in the accumulation and graben to have the tops appear level because the rate of growth of the trees slows with age. A 5 to 20 year difference in age is insignificant on a 200 year old dormant translational landslide.

Translational landslides in the MacKay River valley can be identified by the main scarps behind the landslides that are cliffs up to 20m high. The graben-accumulation structure is usually not visible because the tops of the accumulation blocks have been eroded or leveled because of small slides.

4.4.2 Classification of material in slides

The movements discussed in this chapter are referred to as earth slides rather that rock slides although the slides are in the Clearwater Formation bedrock. This is because most of the material in the Clearwater Formation will disintegrate when placed in water, therefore it would be classified as soil.

4.5 Conclusions

Slide 17-617a is an active translational earth-slide which started to move between 1958 and 1967 along a sheared bentonitic clay layer in the Kca. The results of the air photograph interpretation show that the average rate of movement is about 0.6m/yr or very slow. The point of land that formed what will become Slide 17-617a is surrounded by landslide deposits.

A SLOPE/W (GEO-SLOPE 1994) analysis suggests that the strength of the Kca was could be as low as $\varnothing_r' = 6$ degrees and $c' = 0$ and the cross-bedding strength in the Clearwater Formation is approximately $\varnothing' = 17$ degrees and $c' = 0$ in the current profile for a factor a safety near unity. A SLOPE/W (GEO-SLOPE 1994) analysis suggests that the strength of the Kca could be as low as $\varnothing_r' = 6$ degrees and $c' = 0$ and the cross-bedding strength in the Clearwater Formation is approximately $\varnothing' = 30$ degrees and $c' = 65$kPa in the original profile for a factor a safety near unity.

Slide 10-65c is a dormant translational or compound earth-slide that moved along a surface of rupture in the Kca. More field investigations are required to determine the mode of movement.

Chapter 5 Slides 1953aa, 22-773f and 22-773c, d and e

5.1 Introduction

Slide 1953aa is located at km 8 of the river, Slides 22-773c, d and e are located at km 4.4 of the river and Slide 22-773f is located at km 4 of the river. The slides are accessible by foot from an unmaintained logging road which turns west off the unpaved road to the Fort MacKay landfill. The logging road is marked by an Alberta Forestry sign.

Chapter 5 is divided into 3 sections discussing the landslides which are ordered from the simplest to most complex mode of movement. These discussions are divided into an air photograph interpretation section and a field investigations section. The field investigations section includes the field observations, the groundwater conditions, the soil sampling results and the slide profile. The sections describing each individual slide are followed by a general discussion and conclusions.

5.2 Slide 1953aa: Complex rock topples and rock slides

5.2.1 Air photograph interpretation

Figure 5.2.1 is a photograph of Slide 1953aa taken from a helicopter by on August 20, 1995. Three sets of air photographs are discussed in this section. They are summarized in Table 4.2.1. The air photographs were obtained from Alberta Photo Services (Maps Alberta). Other sets of air photographs were examined, but are not necessary for the interpretation because there are no visible changes between 1953 and 1988.

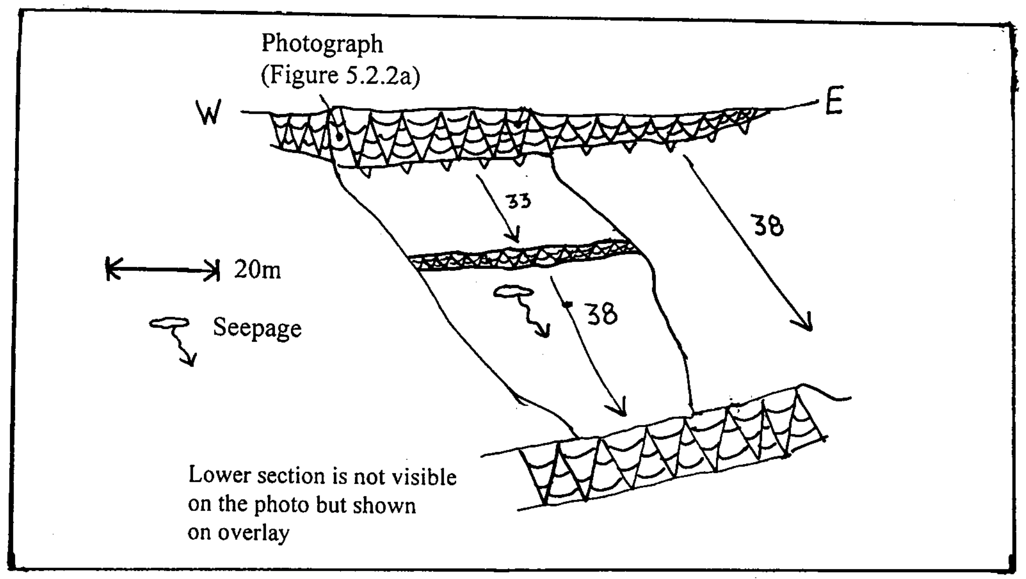


Figure 5.2.1. Photograph of Slide 1953aa. The overlay of the photograph shows the features of the Slide 1953aa. Profile and stratigraphy on Figure 5.2.2b.

Table 5.2.1 Air photographs of Slide 1953aa.

Identification number	Date	Original scale	Source
AS 547 204	1953 09 14	1:15 840	Maps Alberta
AS 3700 220	1988 05 18	1:10 000	Maps Alberta

The air photographs show that the rate of retreat of the crown of the landslide is probably extremely slow (under 16mm/yr, Cruden and Varnes 1996). The centre of the main scarp has retrogressed about 15m over the time the slope has existed. A conservative estimate of the time this slope has existed is approximately 3000 years, therefore the rate of retreat of the crown would be about 5mm/yr.

5.2.2 Field investigations

Groundwater conditions

There is no surface flow of water toward the crown of the landslide. The valley rim in the area around Slide 1953aa is higher than the muskeg and marshes 150m behind the crown. I do not believe that the raised rim is caused by valley rebound because the feature is not common in the lower MacKay River valley. Surface water is drained from the muskeg and marshes by a stream in a valley that is adjacent to the upstream flank of Slide 1953aa. The valley is shown in Figure 5.2.1.

There are signs of seepage coming out of the oil sands in the centre of the slope in a bitumen-free sand layer below a cemented sandstone layer. The seepage and the cemented sandstone layer which forms a small cliff are shown in Figure 5.2.1. The muskeg and marshes behind the crown of the landslide indicate that there is probably a perched water table, otherwise the slope would be wet. The cemented sandstone layers, clay-rich layers and bitumen-rich layers of the upper member and middle member have low permeabilities forming a cap over the underlying bedrock. The seepage from the Slide 1953aa is from the perched water table. In some areas behind the crown, the rock above the high-permeability sand layer is probably leaking because of lower bitumen contents, jointing or other discontinuities. There is no till overlying the area, therefore infiltration into the bedrock is probably higher than for other areas in the river valley.

Field observations

The first observation is that the upper oil sands slopes are vertical. I believe these slopes are in the upper marine McMurray Formation. Approximately half of the upper sequence is cemented sandstone. I believe that the sand is cemented together with silica because the sands in the McMurray Formation are about 95 percent quartz. There are no signs of blocks of oil sands toppling, but the flanks of the landslide contain rock that is jointed by exfoliation fractures. It is probable that the material in the centre of the main scarp of the landslide has been removed by the process of toppling. This would explain the scalloped main scarp (Dusseault 1977). Figure 5.2.2a is a photograph of the exfoliation fractures in the oil sands on the upstream flank of the landslide. The location of the photograph is shown in Figure 5.2.1.

The main scarp of the landslide is scalloped because the seepage at the centre of the slide would trigger movements at the centre of the slide Rock-slides and rock-topples will start above the seepage and slowly radiate out, enlarging the landslide. Most of the material moved is at the centre of the slide and less at the flanks. The slopes on site have probably been moving for thousands of years. Vegetation cannot re-establish because the south-facing slopes are very hot during the summer and very steep. Another explanation is that the light oils in the bitumen evaporates leaving an asphalt-like coating

Figure 5.2.2a. Exfoliation fractures in the oil sands on the upstream flank of Slide 1953aa. The tape on the left side of the photograph is for scale.

over the slopes. Roots cannot penetrate the asphalt-like layer. Slopes cut in the mine pit are not exposed long enough to allow this process to occur.

There only a few small slabs (under $0.5m^3$) on the beach below the limestone cliffs. The accumulation is small because the colluvium is eroded each year by the river during the periods of high flow. The remainder of the colluvium accumulates on the slope above the limestone cliffs. Some debris accumulates behind tree roots at the top of the cliff.

Slide profile

Figure 5.2.2b is the centre profile of Slide 1953aa. A trace of the profile is shown in Figure 5.2.1. The following slide dimensions are measured from the profile. Cruden and Varnes (1996) described the procedure for measuring these dimensions. I have considered the landslide as one movement in these measurements when it is really a series of small movements (under $0.5m^3$ for the rock slides and under $15m^3$ for the topples).

- Volume of the landslide (including a 10 percent swell factor): $5.5 \times 10^4 m^3$.
- Width of main scarp: 40m
- Height of exposed main scarp: 8m
- L_r, maximum length of rupture surface: 90m
- L_d, length of displaced material (accumulations of talus): 60m
- L, total length: 120m
- W_r, width of rupture surface: 40m
- W_d, width of displaced material: 20m
- D_r, maximum depth to surface of rupture: 10m
- D_d, maximum depth of displaced material: 3m

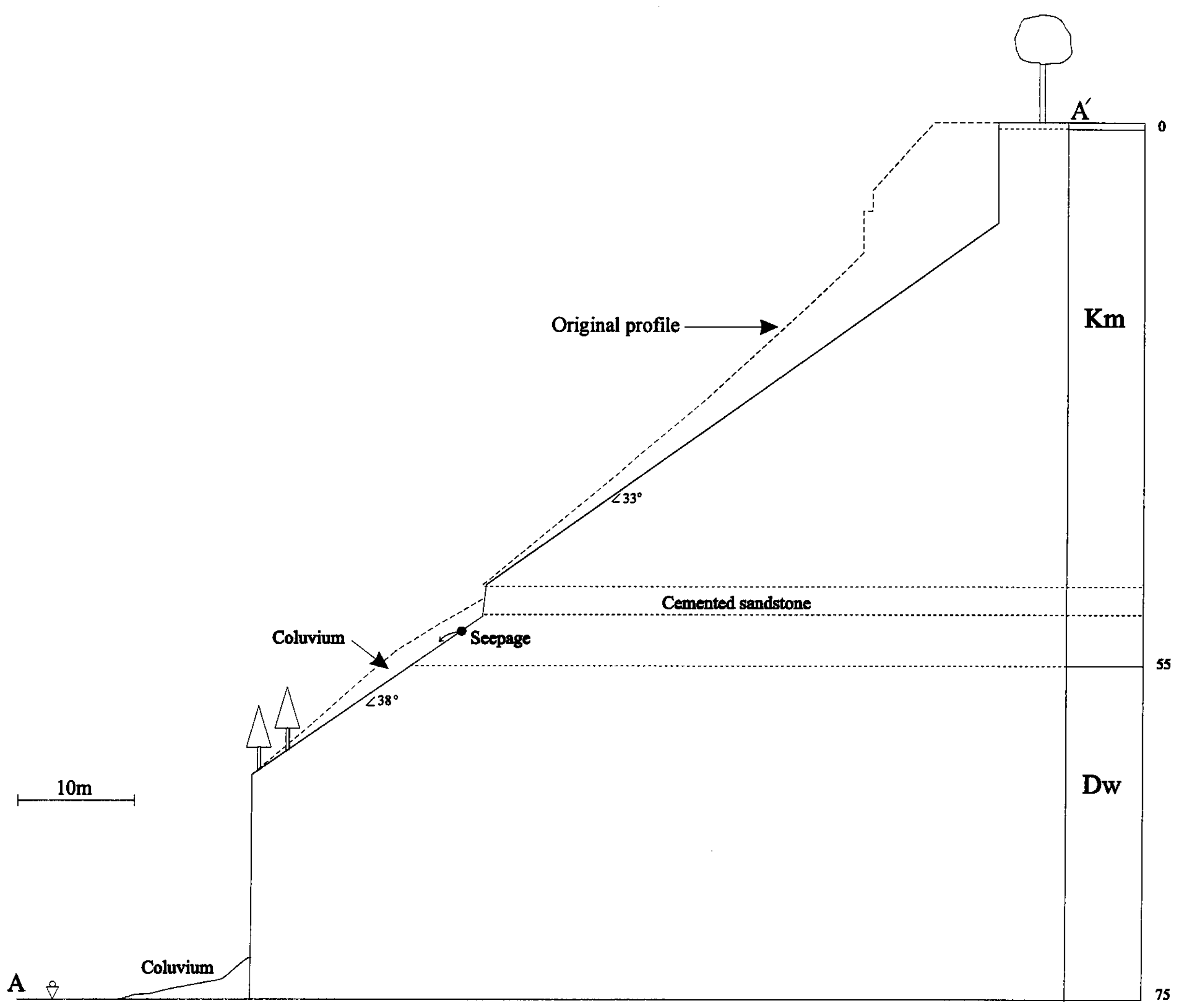


Figure 5.2.2b. Centre profile of Slide 1953aa.

- Travel angle (tip to crown): 50 degrees

The travel angle of 50 degrees is extremely high for an active landslide, although the movements on this slide are shallow. This demonstrates the strength of natural slopes in the McMurray Formation.

5.3 Slide 22-773f: Complex rock topples and rock slides and composite debris -slide debris-flow

5.3.1 Air photograph interpretation

Figure 5.3.1a is a photograph of Slide 22-773f taken from an airplane by Gord McKenna on May 8, 1995. The area surrounding Slide 22-773 is shown in Figure 5.3.1b on an overlay of air photograph AS 3305 276. Four sets of air photographs are discussed in this section. They are summarized in Table 5.3.1. These air photographs were obtained from Alberta Photo Services (Maps Alberta) and Western Photogrammetry.

Table 5.3.1 Air photographs of Slide 22-773f.

Identification number	Date	Original scale	Source
AS 547 204	1953 09 14	1:15 840	Maps Alberta
AS 3305 276	1986 05 17	1:5 000	Maps Alberta
AS 3833 211 to 226	1988 07 04	1:15 000	Maps Alberta
WP-9302-23-773	1993 05 10	1:10 000	Western

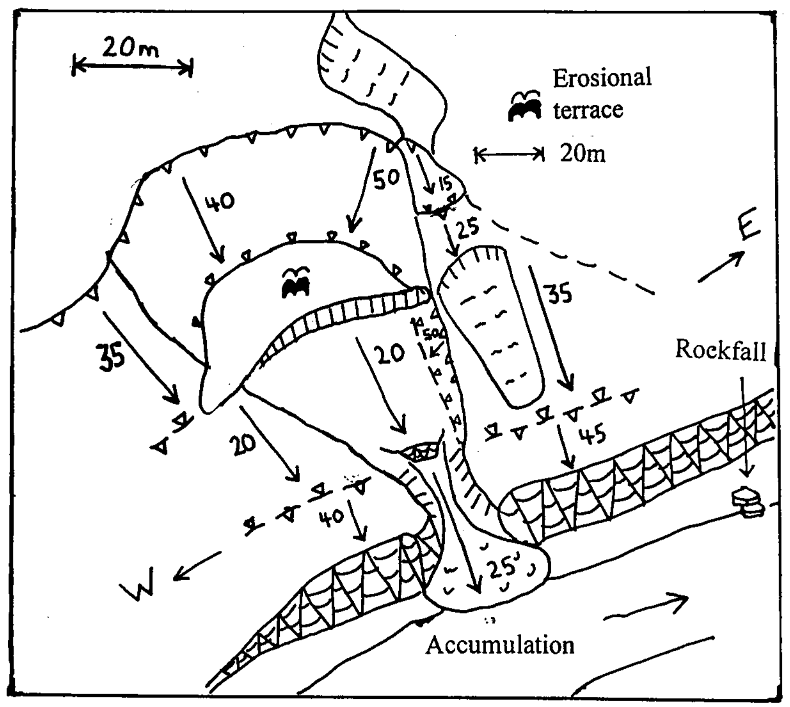


Figure 5.3.1a. Photograph of Slide 22-773f. The overlay of the photograph shows the features of Slide 22-773f. Profile and stratigraphy on Figure 5.3.1a.

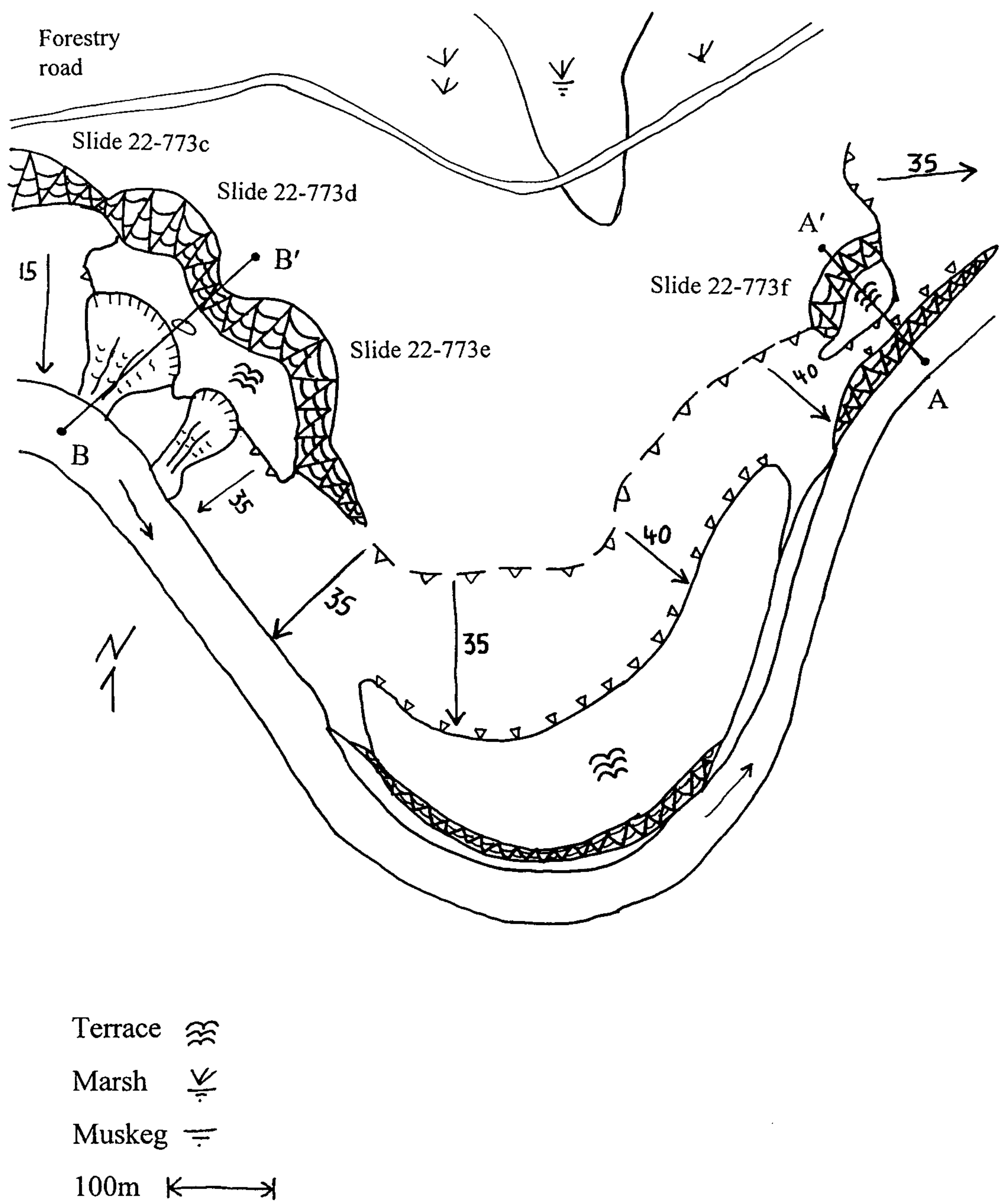


Figure 5.3.1b. Overlay of air photograph AS 3305 276 (Alberta Photo Services).

There were no movements on the site of the Slide 22-773f between 1953 and 1988. The river terrace deposits moved between 1988 and 1993 in a composite debris-slide debris-flow because the zone of accumulation is visible on the 1993 air photographs. Figure 5.3.1b shows the landslide site before the movement occurred. The rate of movement was probably rapid (3m/min to 5m/s, Cruden and Varnes 1996). There were no movements in the upper oil sands slope between 1953 and 1993.

5.3.2 Field investigations

Groundwater conditions

The site was visited on June 27, 1995 after 5 days of continuous rain. A small stream was flowing down the centre of the slide and across the zone of accumulation. The source of the stream was water stored in the river terrace deposits. The stream was not flowing when the site was re-visited on July 19, 1995 after a week without precipitation.

There was no seepage observed in the upper oil sands slope. It is possible that there is a zone of seepage underneath the river terrace deposits, but I cannot verify this hypothesis. The site is dry, therefore the water table in the area is perched (Section 5.3.1).

Field observations

The flat area below the upper oil sands slope is a terrace because there are large slabs of ice-rafted siltstones (about 20cm thick, 100cm long and 150 cm wide) derived from the Clearwater Formation in the deposits. The terrace is probably an erosional unpaired terrace (Section 3.3). There is very little colluvium from the upper slope on the river terrace indicating that the frequency of movements on the upper slope has decreased since the terrace was deposited. The scalloped main scarp on the upper slope was probably formed when the river was at the toe of the slope thousands of years ago.

Vegetation has not grown on the south-facing upper slope because of the steep angle, asphalt-like coating and sunlight exposure.

The debris in the zone of accumulation includes oil sand fragments and paleosol picked up during movements and trees from the terrace. The slide is a composite debris-slide debris-flow because there are slickenslides in the limestone below the river terrace. Debris sheared the limestone as it slid over the outcrop.

Slide profile

Figure 5.3.2 is the centre profile of Slide 22-773f. The trace of the profile is shown in Figure 5.3.1b. The following slide dimensions are measured from the profile for the composite debris-slide debris-flow. Cruden and Varnes (1996) described the procedure for measuring these dimensions.

- Volume of the landslide (including a 10 percent swell factor): $1.0 \times 10^3 m^3$.
- Width of main scarp: 35m
- Height of exposed main scarp: 5m
- L_r, maximum length of rupture surface: 20m
- L_d, length of displaced material: 45m
- L, total length: 60m
- W_r, width of rupture surface: 30m
- W_d, width of displaced material: 30m
- D_r, maximum depth to surface of rupture: 8m
- D_d, maximum depth of displaced material: 5m
- Travel angle: 28 degrees

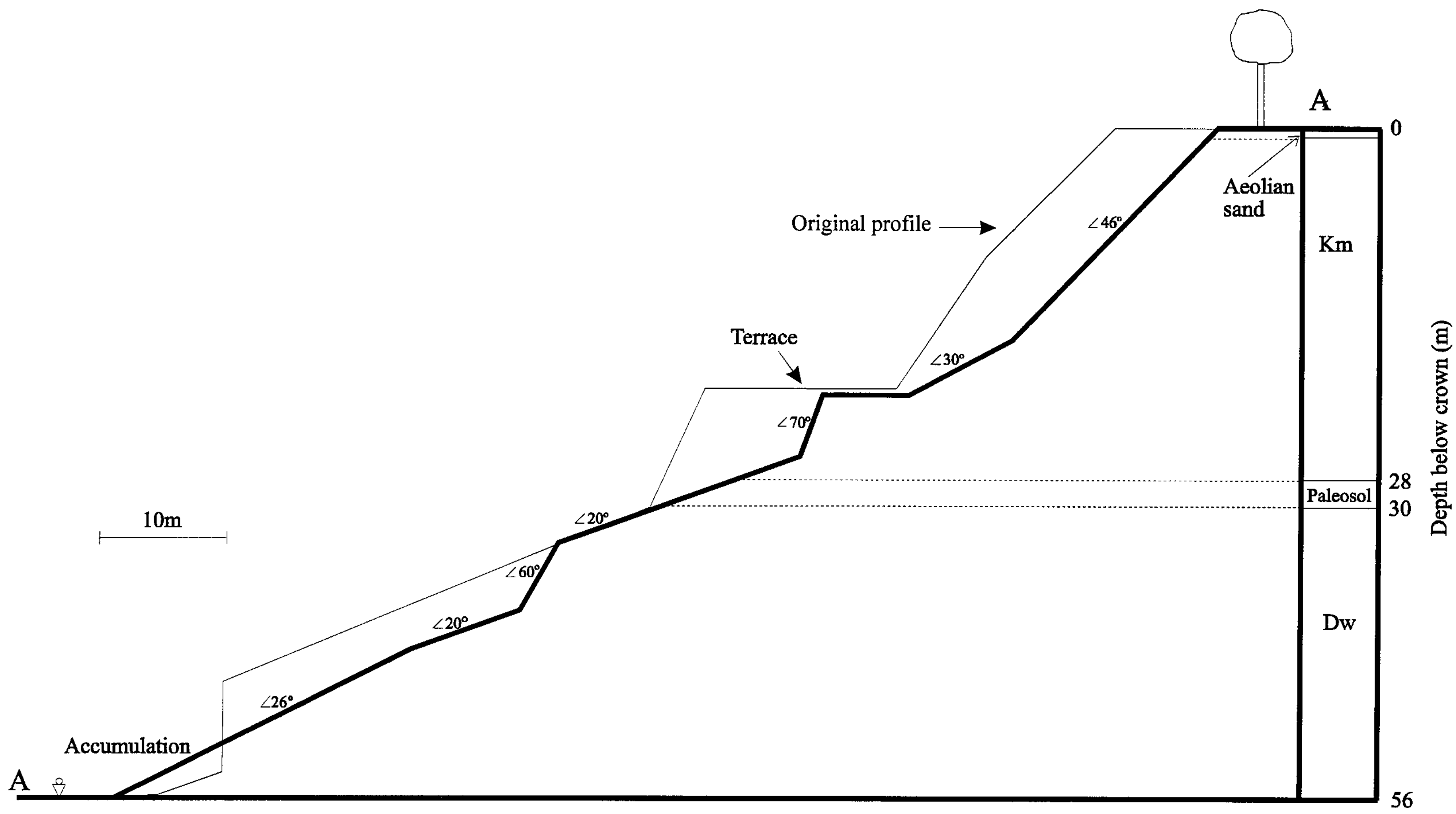


Figure 5.3.2. Centre profile of Slide 22-773f.

5.4 Slides 22-773c, d and e: Complex rock topples and rock slides and retrogressive shallow earth-slide earth-flows

5.4.1 Air photograph interpretation

Each landslide in this section is actually two movements, but the movements are classified together because one movement is above the other movement. The upper movement is in the oil sands of the Middle and Upper McMurray Formation on the upper slope and is similar to Slide 1953aa. The lower movement is in the basal clays on the lower slope below the scarp of the river terrace. Figure 5.4.1 is a photograph of Slides 22-773d and e taken from a helicopter on August 30, 1995. Slide 22-773c is to the left, but is overgrown and dormant. Five sets of air photographs are discussed in this section. They are summarized in Table 5.4.1. The air photographs were obtained from Alberta Photo Services (Maps Alberta) and Western Photogrammetry.

Table 5.4.1 Air photographs of Slide 22-773c, d and e.

Identification number	Date	Original scale	Source
AS 547 204	1953 09 14	1:15 840	Maps Alberta
AS 2170 69	1980 10 07	1:10 000	Maps Alberta
AS 3305 276	1986 05 17	1:5 000	Maps Alberta
AS 3833 211 to 226	1988 07 04	1:15 000	Maps Alberta
WP-9302-23-773	1993 05 10	1:10 000	Western

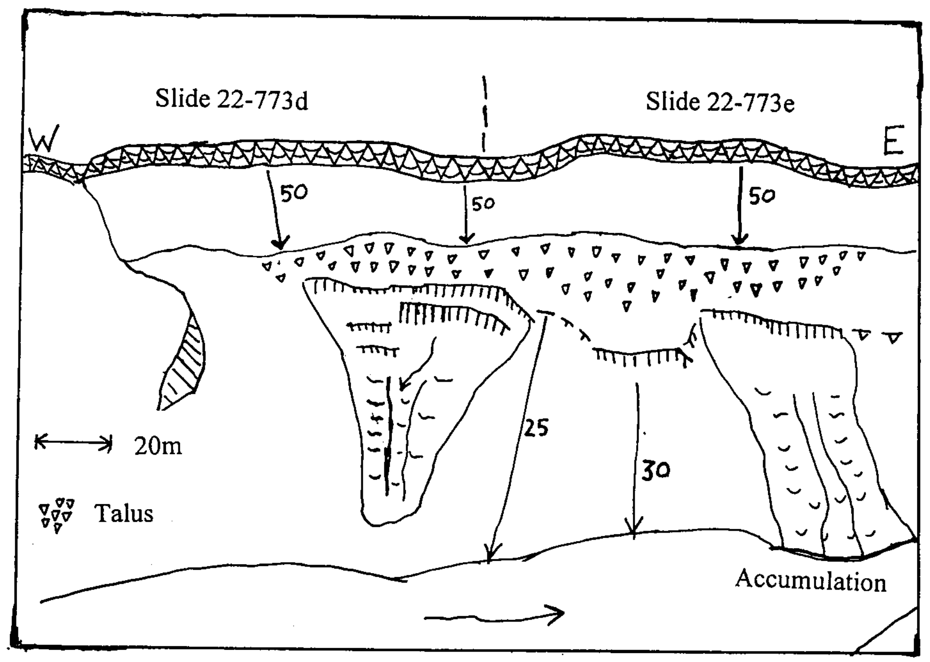


Figure 5.4.1. Photograph of Slides 22-773d and e. The overlay of the photograph shows the main features of Slides 22-773d and e. Profile and stratigraphy on Figure 5.4.2c.

The 1953 and 1993 air photographs show that there has been no retreat of the main scarps of the upper slopes of slides 22-773c, d or e. Between 1986 and 1993, there has been a movement halfway up the upper slope of Slide 22-773e. A slab of oil sands has slid down the slope (Section 5.4.2, field observations). The 1988 air photographs provide no information because the base of the slope is hidden by a shadow. Slide 22-773c is dormant and overgrown in the 1953 air photographs.

The lower slopes of Slides 22-773d and e are active on the 1953 air photographs. The scale of the photographs and errors associated with scaling distances off them make it difficult to estimate the rate of retreat of the crowns of the lower landslides. I estimate that the crowns of both slides have retreated less than 5m over the last 30 years. The active portion of the lower Slide 22-773d has decreased over the past 33 years. The 1953 and 1986 air photographs show that there was less vegetation on the upstream flanks of the earth-slide earth-flow than in the 1993 air photographs.

5.4.2 Field investigations

Groundwater Conditions

The site was visited after a snowfall making it difficult to determine if there was any zones of seepage in upper slopes of Slides 22-773d or e, although some small seeps were visible on both slopes. There was only a few trickles of water (less than 1litre/min) running down the slopes of the lower landslides. This water comes from the talus, river terrace sands and small ponds and flows down the colluvium deposited by the retrogressive earth-slide earth-flows.

Field observations

All 3 landslides are on south facing slopes. Slide 22-773c is overgrown and dormant and is not discussed in detail. Figure 5.4.2a is a photograph looking down across the downstream flank of Slide 22-773d showing active topples in the Upper McMurray

Formation. The photograph was taken by Gord McKenna on October 25, 1995. The topples are in the upper 3 to 5m of the slope and are probably caused by freeze-thaw cycles in vertical exfoliation fractures. In the Middle McMurray Formation, the slope is approximately 50 degrees and the mode of movement is rock sliding. Figure 5.4.2a shows that the talus from the rock topples and rock slides can travel up to 40m from the base of the upper slope. There is a slight depression at the base of the slope and a ridge of blocks at the edge of the terrace. This is probably a protalus rampart that is described as “ridges of blocks at the foot of the larger talus heaps”(Bryan, 1934, p.656). A protalus rampart is created when spring topples roll or slide along the snow accumulated at the base of the upper slope.

I believe that the level ground at the base of the upper slopes is a 20m river terrace (T2). There is a 1m cover of oil sands above the pond muds that are visible in the scarp of the retrogressive shallow earth-slide earth-flows at the edge of the terrace. Landsliding has not created the level ground at the base of the upper slopes because the surface of rupture would be in the weaker pond muds below the oil sands. There are no fluvial deposits on the terrace, only a sandy soil with pieces of weak oil sands that resembles the colluvium on the overgrown upstream flank of Slide 22-773d. Only one shield cobble was found in three test pits excavated to 0.7m depth, but Shield pebbles are rare in the area because the till was stripped from the bedrock by the proposed Glacial Lake Agassiz open channel paleoflood 9900 yr BP(Smith and Fisher 1993). It is possible that there are terrace deposits below the bottom of the test pit. The only deposit above bedrock is a 1m veneer of aeolian sand. Another explanation is that the terrace is an erosional terrace, but the other 15 to 20m terraces upstream have thick (5 to 7m) fluvial deposits. There is a similar feature 200m downstream that I have also classified as a T2 terrace (Figure 5.3.1b).

Figure 5.4.2b is a photograph of a large slab of oil sands about 3m thick, 20m wide and 5m long. The photograph was taken on October 25, 1995.

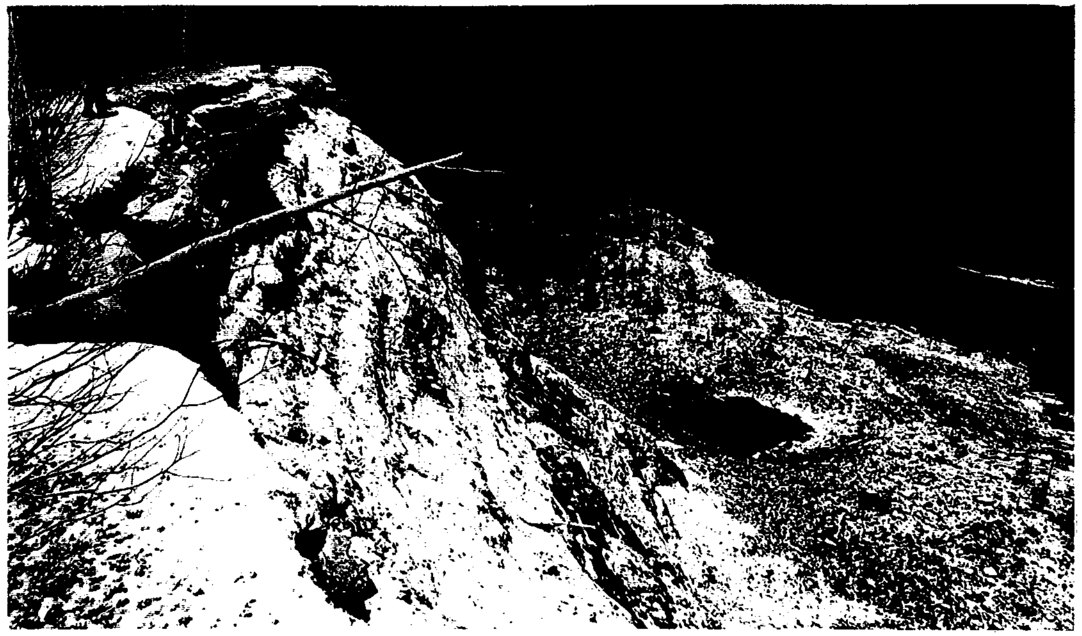


Figure 5.4.2a. Photograph looking down across the downstream flank of Slide 22-773d. I am in the top left corner for scale.

Figure 5.4.2b. Photograph of the block of oil sands that slide off the upper slope of Slide 22-773e. I am in the centre of the photograph for scale.

The slab slid between 1986 and 1993 (Section 5.4.1). It is also possible that the slab is related to a deeper movement in the pond muds although I cannot verify this without more field work.

The retrogressive shallow earth-slide earth-flows on the lower slopes of Slides 22-773d and e have tension cracks behind the crown of the last movement indicating that the slides are still retrogressing. The trees behind the main scarp of Slide 22-773e have a drunken appearance. Gord McKenna observed that a tree growing on the most recent movement was tilted at 20 degrees for the first 5m and straight for the last 0.7m. The profile of the tree suggests that the crown of the slide was stable for about 30 years and the movement was fairly rapid. The straight section of tree at the top shows that the block has not rotated over the past few years, otherwise the top section of the tree would be curved.

The retrogressive shallow earth-slide earth-flows are probably triggered by the following processes:

- The material behind the main scarp of the previous movement is softened by rain and frost penetration.
- The terrace is being slowly loaded by the accumulating talus and
- The overlying material in the terrace above the pond muds is a maximum of 3m thick, therefore much more water infiltrates into the pond muds than in the upper slopes behind the scarp,

The crown of the dormant retrogressive earth-slide earth-flows on the lower slopes of Slide 22-773c is at the base of the upper oil sands slope. The terrace in that area was about 10m less in width than in front of Slides 22-773d and e, but I believe that the crowns of the active earth-slide earth-flows will retreat to the base of the upper slopes

Soil Sampling

Two samples of pond muds (basal clays) were taken from the main scarp of the retrogressive earth-slide earth-flows of Slide 22-773d. Table 5.4.2a shows the results of the Geotechnical testing performed at Syncrude's geotechnical laboratories. The pond muds are soft to very soft, massive and highly plastic.

Table 5.4.2a. Results of geotechnical testing on pond muds.

Sample number	w (%)	L.L. (%)	P.L. (%)	P.I.(%)	Silt (%)	Clay (%)	Activity
MRTAD4	27	37	16	21	51	49	0.47
MRTAD5	34	42	18	24	47	53	0.47

Seven samples of the sands on the terrace, slopes and behind the crown of Slide 22-773E were taken. Table 5.4.2b shows the results of the Geotechnical testing preformed at Syncrude's geotechnical laboratories.

Table 5.4.2b. Results of grain size analysis on oil sands around the landslide sites.

Sample number	Location	Oil (%)	Water (%)	Solids (%)	Grave l (%)	Sand (%)	Fines (%)
MRTAD1	Terrace 22-773e, H_f	3	9	88	19	76	5
MRTAD2	Terrace 22-773e, H_f	6	7	87	21	77	2
MRTAD3	Terrace 22-773e, H_f	11	0	89	na	na	na
MRTAD6	Slope colluvium 22-773d, H_c	2	2	96	7	83	10
MRTAD7	Slope colluvium 22-773d, H_c	2	3	95	1	83	16
MRTAD8	Crown of 22-773e, H_{ae}	na	na	na	1	83	16
MRTAD9	Crown of 22-773e, H_{ae}	1	9	90	25	69	6

The soil samples are similar because they are probably all derived from the oil sands. Some samples have a higher gravel content because the samples were not pulverized before the grain size analysis. The gravel content within a sample is related to how much weathering a soil has undergone. As an example sample MRTAD8 is taken from the upper 30cm of soil and sample MRTAD9 is taken from 50cm below the ground surface. Sample MRTAD8 has no clumps of oil sands, but sample MRTAD9 has 25 percent oil sand clumps.

Slide profile

Figure 5.4.2c is the upstream flank profile of Slide 22-773d (Dusseault 1977). The trace of the profile is shown on Figure 5.3.1b. There was not enough data collected to estimate the measurements of the landslide. The plan view of the retrogressive shallow earth-slide earth-flow shows that the slide is also enlarging on the flanks.

It is not possible to accurately determine the rate of retreat of the crown of the upper slopes of Slides 22-773d and e because the age of the terrace that the talus is deposited on is unknown. I estimate that the rate is extremely slow because the volume of talus on the terrace is quite low. There is about $100m^3$ of talus in the slope profile and the slope is 35m from top to bottom. If the soil was evenly replaced on the slope it would be 3m thick. If the terrace is 3000 years old then the crown has retreated 1mm per year. The actual velocities of the movements are probably very rapid to extremely rapid (3m/min to above 5m/s, Cruden and Varnes 1996).

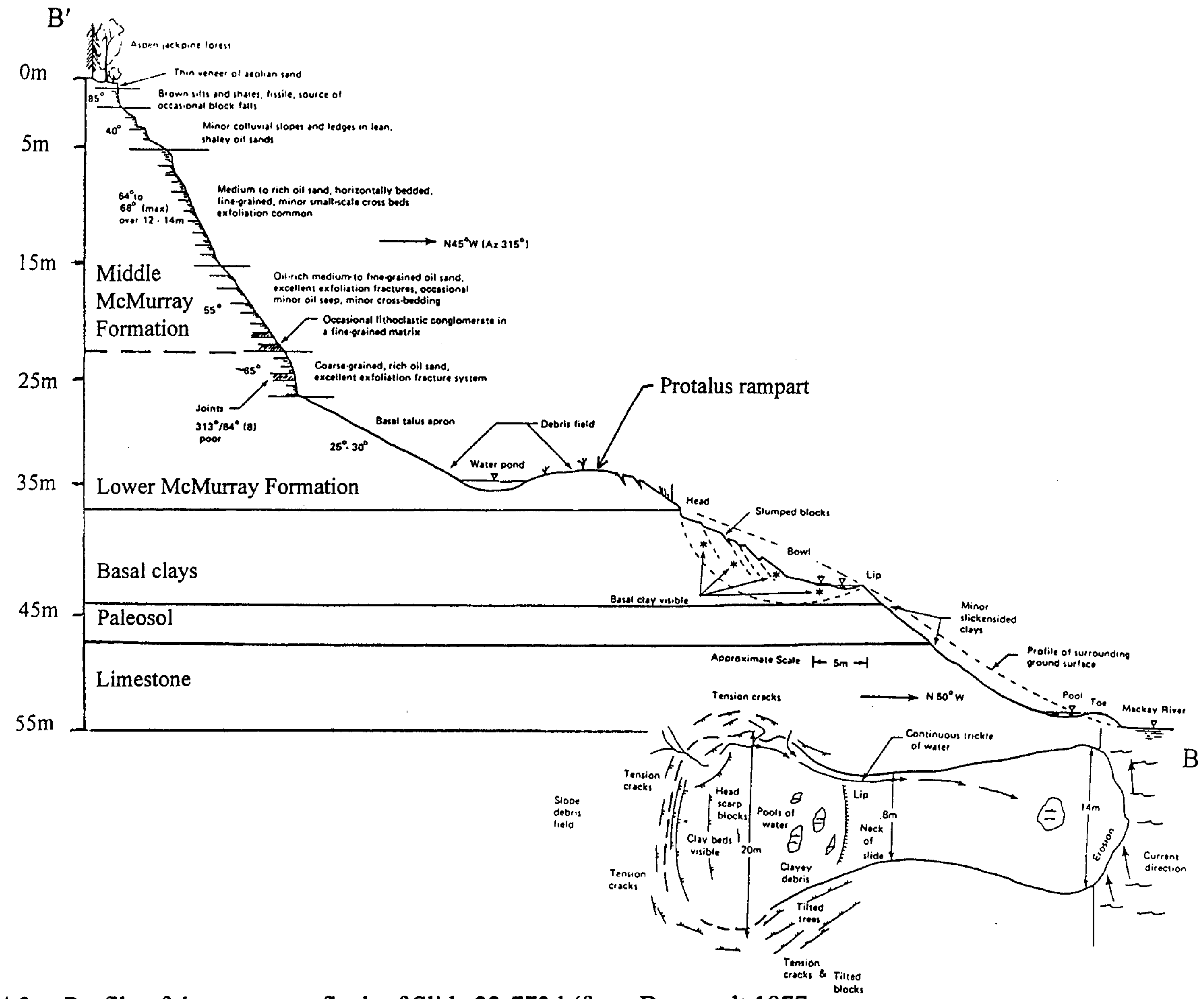


Figure 5.4.2c. Profile of the upstream flank of Slide 22-773d (from Dusseault 1977, Slopes 7 and 7a, pp. 316-317).

5.6 Discussion

All the landslides discussed in this chapter have scalloped main scarps in the Upper and Middle McMurray Formation. Slide 22-773f has movements in river terrace deposits midway down the slope. Slides 22-773c, d and e have movements in the pond muds below what I believe to be a river terrace.

Dusseault (1977) made several conclusions based on his studies of natural slopes in the McMurray Formation. I agree with most of his conclusions, but disagree on the following points:

1. Seepage from the face of the active slopes "are solely of surface and near surface origin" (Dusseault 1977, p.86): I believe that a portion of the seepage is from the recharge of discontinuities near the surface, but some of the seepage flows through discontinuities and high permeability layers to daylight at the face of the slope. This explains the scalloped main scarps of the slides in the upper and middle members of the McMurray Formation. Movements start at the point of seepage and radiate out, enlarging the slide,

2. "Slopes containing significant quantities of basal clay (pond muds) display characteristic morphologies such as bimodal slopes, scalloped back-scarps (main scarps) and basal landsliding"(Dusseault 1977, p.293): The scalloped main scarps are caused by a zone of seepage in the center of the slide, otherwise the statement is true. There are retrogressive shallow earth-slide earth-flows in the basal clays (basal landsliding) and

3. There are block falls in the McMurray Formation (Dusseault 1977, p.77). The rock topples then may bounce or slide.

The remainder of Dusseault's (1977, p.293) conclusions have stood the test of time. These conclusions include:

1. "Oil-free coarse-grained oil sand may form very steep slopes up to 70m in height" (Dusseault 1977, p.90),

2. "All oil sands slopes show few well developed diagenetic joints, but numerous well-developed exfoliation (stress-relief) joints" (Dusseault 1977, p.90) and

3. There are "no deep-seated rotational failures in intact oil sands" (Dusseault 1977, p.293).

5.7 Conclusions

Slide 1953aa (Section 5.2) is a complex rock topple and rock slide which has probably been active for several thousand years. The rate of retreat of the crown is extremely slow (under 6mm/year) but the rates of movement of individual topples and slides are very rapid (3m/min to 5m/sec). The landslide is triggered by a zone of seepage midway up the slope. The scalloped-shaped main scarp was created as the landslide enlarged from the zone of seepage. The water table in the area is perched. Water infiltrates through discontinuities in the otherwise impermeable upper member of the McMurray Formation and bitumen-rich middle member of the McMurray Formation into bitumen-free high-permeability sand zones.

Movements in Slides 22-773c, d, e and f are identical to Slide 1953aa, but these slides have additional movements in or below river terraces at the base of the upper oil sands slopes. Slide 22-773f (Section 5.3) is a composite debris-slide debris-flow of the river terrace deposits. The movement occurred between 1986 and 1993 at a very rapid rate (3m/min to 5m/sec). The movement was probably triggered by weathering and precipitation.

Slides 22-772c, d and e (Section 5.4) have movements in the basal clays below an erosional river terrace. The movements are retrogressive shallow earth-slide earth-flows which have a rapid to very rapid rate of movement (1.8m/hr to 5m/sec). Contributing factors to the movements include: saturating the clays because of infiltration through the thin terrace sediments, loading of the terrace by talus and softening by weathering and rain.

There were no deep seated movements in the oil sands slopes and the McMurray Formation forms very steep slopes up to 70m high. These two points confirm Dusseault's (1977) observations of the geomorphology of oil sands slopes.

Chapter 6 Slide 23-806c

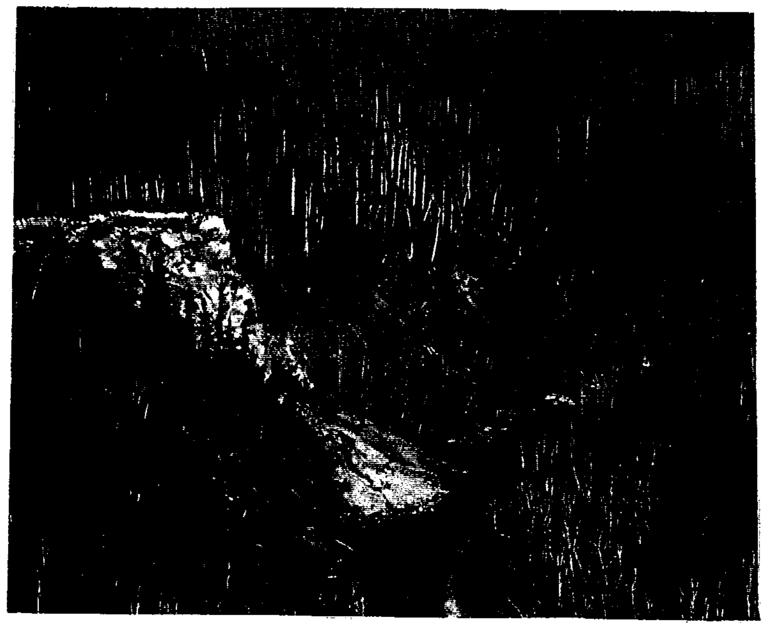
6.1 Introduction

Slide 23-806c is located at kilometre 16 of the MacKay River. Slide 23-806e is also discussed in this section because it is 500m downstream from Slide 23-806c and has the same lithology and mode of movement. Access to Slide 23-806c and Slide 23-806e is currently by helicopter or canoe.

Chapter 6 is divided into the following sections: 6.2) Air photograph interpretation, 6.3) Field investigations, 6.4) Stability analysis, 6.5) Discussion and 6.6) Conclusions. The field investigations section is further divided into the following sections: 6.3.1) Field observations, 6.3.2) Groundwater conditions, 6.3.3) Soil sampling and 6.3.4) Slide profile.

6.2 Air photograph interpretation

Six sets of air photographs are discussed in this section. They are summarized in Table 6.2. The air photographs were obtained from Alberta Photo Services (Maps Alberta), Western Photogrammetry, North West Survey Corporation International Limited and Syncrude files. The source of the air photographs obtained from Syncrude files is unidentified. Figure 6.2a is a photograph of Slide 23-806c taken from an airplane on May 8, 1995 by Gord McKenna of Syncrude Research. Figure 6.2a includes an overlay of the photograph that shows the features of Slide 23-806c. Figure 6.2b shows the area surrounding Slide 23-806c on an overlay of air photograph WP-9117-23-806.



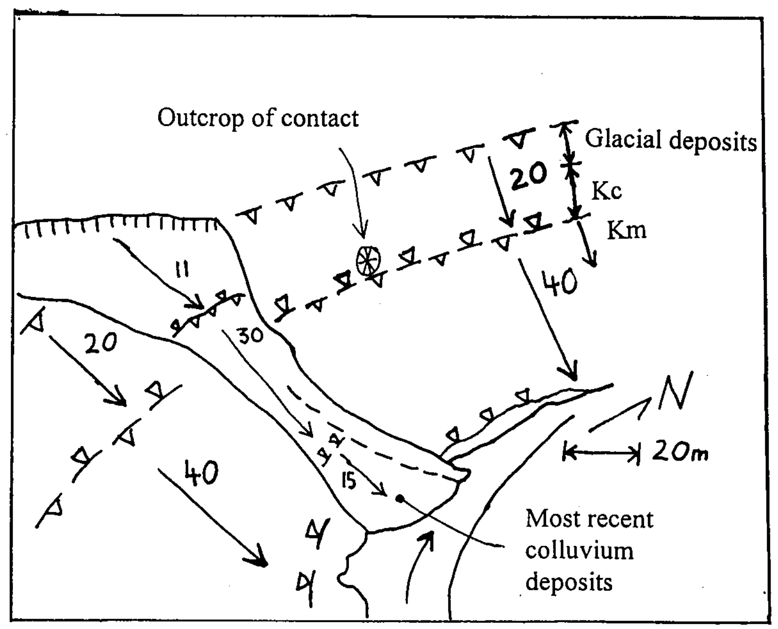


Figure 6.2a. Photograph of Slide 23-806c. The river in front of the zone of accumulation is 20m wide at its narrowest point for scale. The overlay of the photograph shows the features of Slide 23-806c.

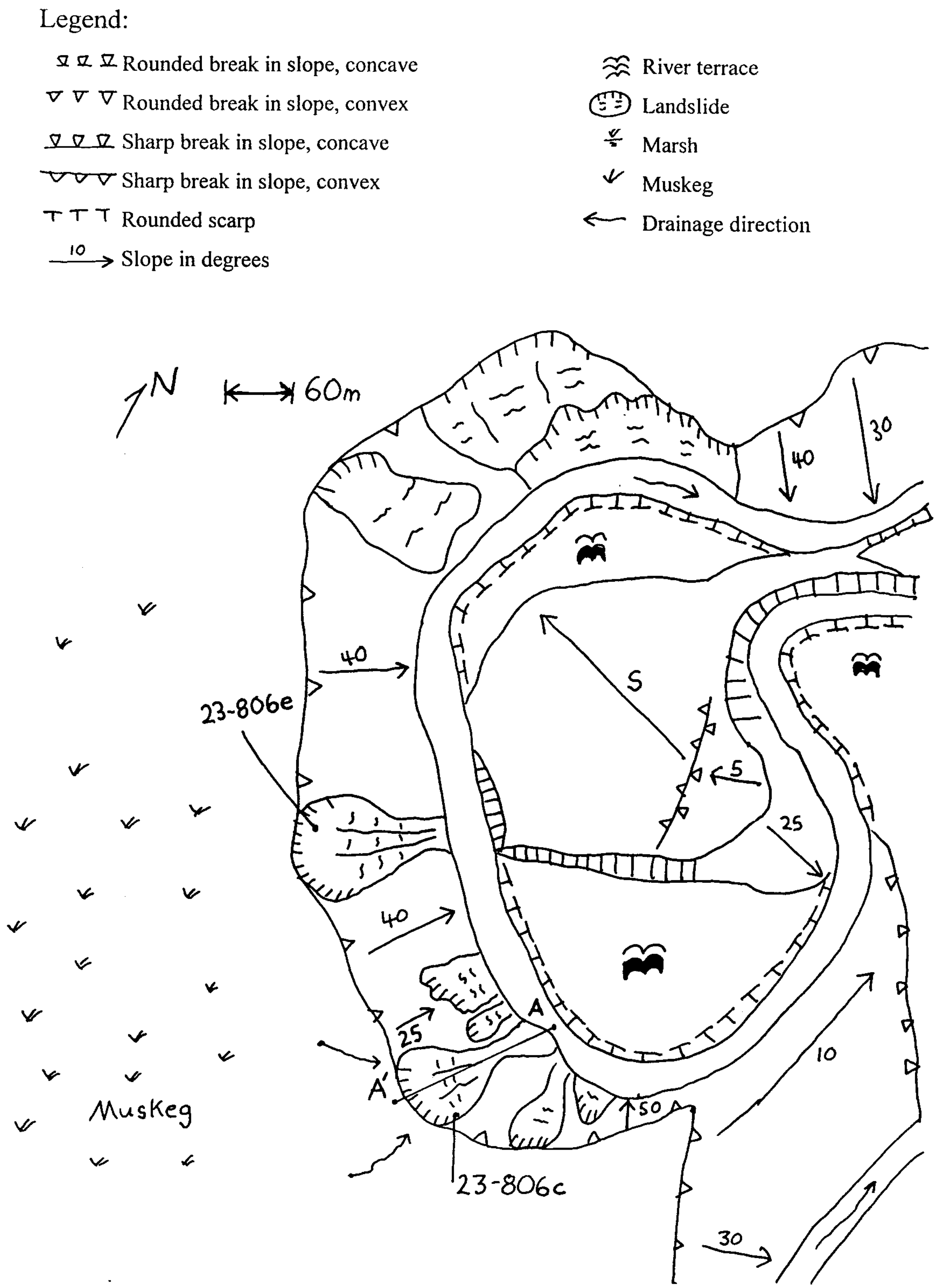


Figure 6.2b. Overlay of air photograph WP-9302-23-0806.

Table 6.2 Air photographs of Slide 23-806c.

Identification number	Date	Scale	Source
AS 545 73	1954 10 05	1:15 840	Maps Alberta
A16909-171	1958?	1:32 680	Unknown
AS 964 205	1967 08 31	1:31 680	Maps Alberta
AS 1203 11 (infrared)	1972 08 22	1:21 120	Maps Alberta
NW68881	1981 08 07	1:60 000	North West
WP-9302-23-806	1991 10 18	1:10 000	Western

Slopes in the oil sands upstream and downstream of Slide 23-806c stand between 40 and 50 degrees and the slopes in the units above the oil sands stand between 20 and 30 degrees. Figure 6.2a shows the steep oil sand slopes that have no vegetation and the slopes in the other deposits that have vegetation.

On the 1953 air photographs, Slide 23-806c is only a small earth-slide earth-flow approximately 200m^2 in area at the rim of the valley. The zone of accumulation extends approximately halfway down the slope and the material that has moved is probably limited to the surficial glacial sediments. Slide 23-806e is still active on the 1953 air photograph, but is starting to overgrow with vegetation. The zone of accumulation that extended into the river has been eroded away and now forms a beach along the base of the slope and deposits on a gravel bar 100m upstream from Slide 23-806a. Drainage in the area appears to be over the crest of Slide 23-806e.

On the 1958 air photographs, Slide 23-806c appears to be the same size as in 1953. Slide 23-806e is dormant and vegetation is growing on the scarps and body of the slide. Drainage still appears to be toward Slide 23-806e, but there is a thinning of the trees between the muskeg behind the landslides and the scarp of Slide 23-806c possibly indicating a change in the direction of flow of surface water. Figure 4.2.2b shows that there was a dry period between 1958 and 1967 because only two years had precipitation above the mean for 1953 to 1972.

On the 1967 and 1972 air photographs, Slide 23-806c appears to be the same size as in 1953 and Slide 23-806e is now overgrown and dormant. There are no other changes between 1967 and 1972 visible on the 1972 air photograph. Figure 4.2.2b shows that the average precipitation between 1967 and 1972 was above the mean for 1953 to 1992. It is possible that movements were not triggered by the high rainfalls because the surface of rupture of the first rotational earth-slide was formed by the process of softening.

Between 1972 and 1981, Slide 23-806c has enlarged to near its current size. It is probable that actual earth-slide earth-flow occurred several years before 1981 because the tip of the zone of accumulation that would have extended into the river has been eroded away. On the 1981 air photographs Slide 23-806e is almost completely overgrown. Slide 23-806c is now about the same size as Slide 23-806e. The 1981 air photographs are difficult to interpret because of the 1:60 000 scale. The average precipitation between 1967 and 1975 is much higher than the mean precipitation between 1953 and 1992 (Fig. 4.2.2b). The peak precipitation was in 1973 at 666mm, a "beastly" amount (Rev. 13:18). The precipitation data is measured at the Fort McMurray Airport. It is probable that the heavy rains during 1973 triggered the first rotational earth-slide earth-flow

Between 1981 and 1991, there has been another earth-slide earth-flow in the soil forming the crown of the first slide at site 23-806c. Therefore, the slide is retrogressive. A zone of accumulation has been deposited into the river reducing the width of the river channel from 40 to 20m. The southeastern flank and main scarp of the landslide has retrogressed more than the northwestern flank because there appears to be more seepage in this area. The surface drainage in the area appears to be toward the southwestern portion of the main scarp.

6.3 Field investigations

6.3.1 Field observations

Figures 6.3.1a and 6.3.1b are two photographs of Slide 23-806c taken on June 27, 1995. Figure 6.3.1a is a photograph of the zone of accumulation and narrowest portion of the slide taken from midway up the slide profile. Figure 6.3.1b is a photograph of the earth-slide earth-flows on the main scarp of the slide. The trees in the photograph lay against the main scarp of the landslide with their tops pointing toward the crown. The McMurray-Clearwater contact is about 5m above the start of vegetation on the slopes. The toe of the surface of rupture of the first rotational earth-slide earth-flow is above the contact.

The field investigations revealed that since 1991 there have been no new deposits in the zone of accumulation, but there has been some minor retrogression of the top scarp of the landslide in the glacial deposits. Figure 6.2a shows that there are a minimum of 2 flows that deposited colluvium in the zone of accumulation. Small trees have grown on the edges of the zone of accumulation, but the centre portion of the zone of accumulation has been covered with the colluvium from the most recent flow that occurred between 1972 and 1981. In the centre of the zone of accumulation is a dead 1m diameter pine tree that was not uprooted by the earth flow, indicating that the flows were relatively wet and did not contain large blocks of debris. The pine tree died after the shallow roots were covered by colluvium.

Figure 6.3.1a. Photograph of the zone of accumulation and narrowest portion of Slide 23-806c taken from halfway up the profile. The log in the centre of the photograph is approximately 8m long for scale.

Figure 6.3.1b. Photograph of the earth-slide earth-flows on the main scarp of Slide 23-806c. The main scarp is 1-2m high for scale.

The main scarp of the landslide is in the glacial sediments and is retrogressing. Figure 6.3.1b shows the small shallow rotational slides in the glacial deposits. The roots of the trees have rotated towards the crown of the landslide. The wind load on the trees probably cause the trees to tilt away from the river, increasing the driving forces on shallow blocks of glacial sediments. The blocks move when the till becomes sufficiently saturated and softened.

Exposed colluvium in the displaced mass of the slide has some small movements (no greater than $10m^3$) caused by the thawing of frost in the spring. The sandy-clayey silt colluvium is susceptible to frost penetration and is impermeable. In spring, water in the soil cannot escape resulting in increased pore water pressures that trigger thaw-flows.

6.3.2 Groundwater conditions

The marsh behind the slide is the source of seepage to the slide and there is no flow over the top scarp of the landslide. The southeastern portion of the zone of depletion is much wetter than the northwestern portion of the zone of depletion. Salt stains on the soil indicate that there is seepage coming from much of the slide area above the narrowest portion of the slide and the McMurray-Clearwater contact.

Very soft saturated soil and small ponds (10 to $50m^2$) are present in the upper and middle plateaus of the landslide above the McMurray-Clearwater contact (refer to Figure 6.3.4a). The wet zones of the slide feed three small streams that flow through the narrowest portion of the slide onto the zone of accumulation. Flow rates for the streams were estimated at 4 litres/min. It is probable that most of the flow came from surface runoff because there were five days of continuous rain until the day before the landslide was visited. The upper 8m of the glacial sediments in the southeastern flank and the upper 15m of sediments in the northwestern flank were observed to be dry during field visits.

6.3.3 Soil sampling

The grain sizes and index properties of samples taken from the colluvium of Slide 23-806c are summarized in Table 6.3.3.

Table 6.3.3. Grain sizes and index properties of colluvium samples from Slide 23-806c.

Sample number	Location on slide	w (%)	L.L. (%)	P.L. (%)	P.I. (%)	Sand (%)	Silt (%)	Clay (%)
MRTA401	zone of accumulation	23	47	21	26	24	33	42
MRTA402	narrowest portion	22	45	21	24	29	33	38
MRTA406	above 1st rupture surface	18	33	16	17	24	42	27
MRTA407	below main scarp	17	44	22	22	21	38	40

The grain size distribution of the first 3 colluvium samples show that the material that flowed is probably derived from the Kcw Member. The colluvium would have a higher sand content if the soil in the McMurray Formation is also moving. The contact between the Kcw and the upper member of the McMurray Formation is visible in a scarp 30m from the upstream flank of the slide. A clump of trees above the bare upstream oil sands slope and adjacent to the flank of the slide hides the scarp. Figure 6.2a shows the location of the outcrop. Lobb and McMullin (1989) described the contact as gradual, but it is sharp in the scarp. The Kcw is a glauconitic sandy clayey silt and the upper McMurray Formation is a dry fine-grained, bitumen-free, uniform sand with some thin shale layers. It is possible that the first movement involved some McMurray Formation sediments, but the colluvium from the first movement is buried under the centre of the zone of accumulation which was not sampled.

Sample MRTA407 is from the glacial deposits and shows the typical grain size distribution for the Pl_2 glacio-lacustrine deposits. The origin of the colluvium can be determined by colour in the field. The colluvium derived from the glacial sediments has a pinkish-gray colour, whereas the colluvium derived from the Kcw has a dark gray colour.

6.3.4 Slide profiles

Figure 6.3.4 is the centre profile of the landslide that is measured with a inclinometer and 50m tape. Figure 6.2b shows the line of the profile. The original profile is estimated from the profiles of the slopes adjacent to the upstream and downstream flanks of the landslide and the 1953 air photographs. The following slide dimensions are measured from the profile (Cruden and Varnes 1996).

- Volume of the landslide (including a 10 percent swell factor): $5.0 \times 10^4 m^3$.
- Width of main scarp: 95m
- Height of main scarp: 1 to 4m
- L_r, maximum length of rupture surface: 100m
- L_d, length of displaced material: 170m
- L, total length: 175m
- W_r, width of rupture surface: 90m
- W_d, width of displaced material: 60m (in the zone of accumulation)

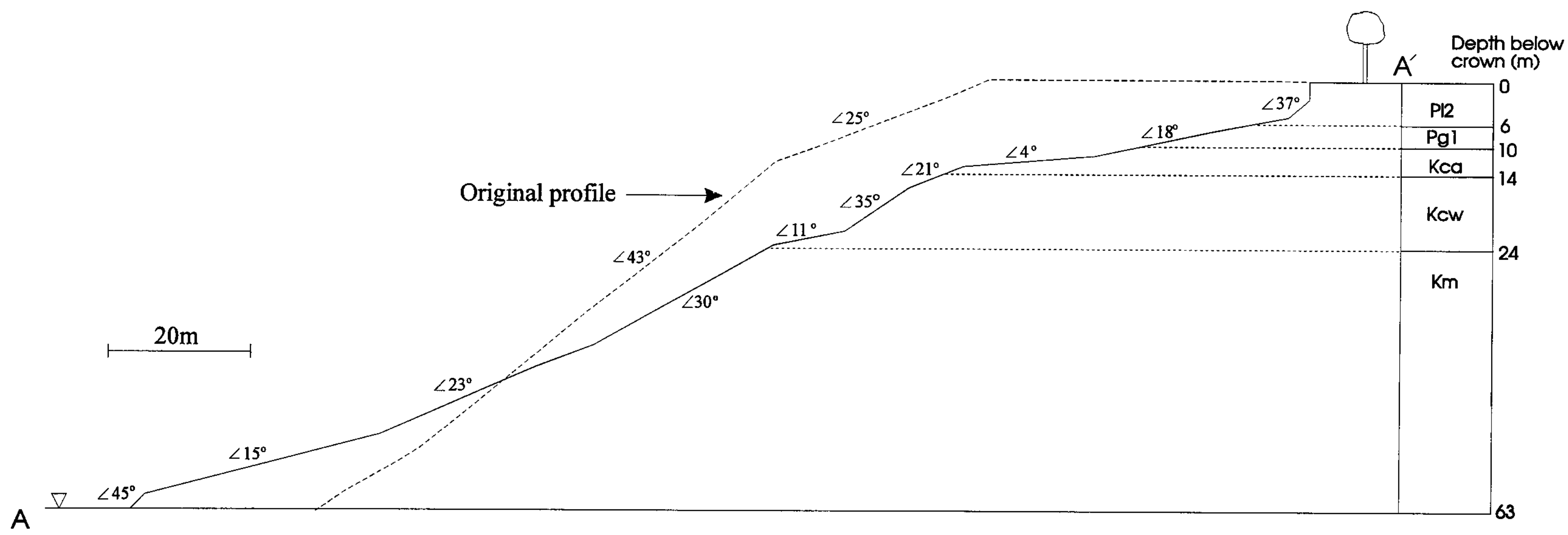


Figure 6.3.4. Centre profile of Slide 23-806c.

- D_r, maximum depth to surface of rupture: 15m
- D_d, maximum depth of displaced material: 12m
- Travel angle: 20 degrees

The actual dimensions of individual movements are smaller. The largest volume of material displaced was probably during the first large movement that occurred between 1972 and 1981. I estimate that the volume of the first movement is half the volume of the landslide. The second movement is probably another third of the volume and the retrogressive shallow earth-slide earth flows account for the remaining sixth of the volume of displaced material.

The rate of movement of the first rotational earth-slide earth-flow was probably in the range of rapid to very rapid (1.8m/hr to 5m/s) (Cruden and Varnes 1996). Velocities of the sliding material increased as it lost strength sliding down the steep slopes of the oil sands. It is unlikely though, that the velocities increased to extremely rapid rates (above 5m/s) (Cruden and Varnes 1996) because the 1981 air photograph shows that the zone of accumulation never reached the opposite bank of the river. There is no evidence that the river was temporarily blocked or that colluvium has been deposited on the opposite bank of the river. The beach and river bank opposite the zone of accumulation are smoothly curved and have the same shape in 1972 and 1981. The first movement caused the crown of the slide to retreat about 20m, based on the results of the Slope/W (GEO-SLOPE 1993) limit-equilibrium analysis in Section 6.4.

The first rotational earth-slide earth-flow would leave a steep scarp that would cause retrogressive movements which probably had the same velocity as the first movement. The retrogressive landslides in the weaker, top 15m of soil (Kca and glacial sediments) caused the crown of the landslide to retreat about 40m between 1972 and 1981. I estimate the retreat from the 1981 air photographs. The rate of retreat of the crown of the Slide 23-806c is in the range of 40 to 4m/yr depending on the date of the first rotational earth-slide earth-flow.

The crown of the slide has retreated about 20m between 1981 and 1991 reducing the rate of retreat to 2m/yr and making the overall average rate of retreat of 4m/yr from 1976 to 1991. The rate of retreat is slowing with time as the ultimate angle of the glacial sediments is approached. In some areas, the back scarp is only 1 to 2m high indicating that the crown will only retreat a few more metres. The velocity of the shallow retrogressive earth-slide earth-flows in the glacial sediments are still rapid to very rapid because the trees on top of the displacing blocks can slide up to 8 metres when the scarp is only 2m high.

6.4 Stability Analysis

The stability analysis is divided into the first movement and the retrogressive movements of the slopes at the landslide site. The first movement stability analysis is performed with SLOPE/W software (GEO-SLOPE 1993) using the Morgenstern-Price limit equilibrium method with piezometric lines to indicate the water table. The pore-water pressures before and during movement are unknown, therefore the accuracy of the analysis depends on an estimate of the water level. I estimate that the water table was at the Clearwater-glacial sediment contact during the first movement. The water table used in the analysis would be about 3m above the top of the saturated soil observed during field visits in June, 1996. I believe the regional water table is perched above most of the McMurray Formation, otherwise the surface of rupture would be deeper, extending into the McMurray Formation.

Figure 6.4 shows the results of the SLOPE/W analysis for the first time movement. The soil properties for the analysis are selected from Tables 4.2.4a and

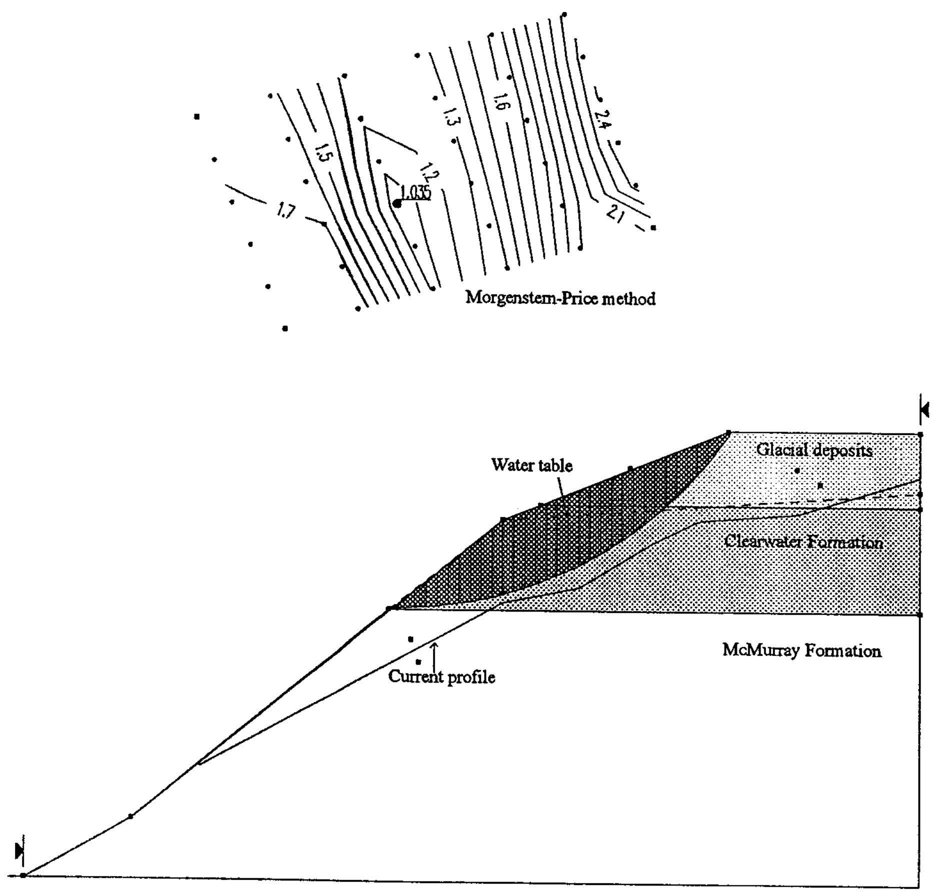


Figure 6.4. Results of the SLOPE/W stability analysis for the first movement of Slide 23-806c.

4.2.4b. The following material properties are used to obtain a factor of safety near unity:

- Glacial sediments: $\varnothing'$= 24 degrees, c′= 0 and $\gamma = 21 kN/m^3$ (Klohn Leonoff 1990)
- Clearwater Formation (Kca and Kcw): $\varnothing'$= 30 degrees, c′= 15kPa and $\gamma = 21.5\ kN/m^3$ (Isaac and Dusseault 1984)
- McMurray Formation: $\varnothing'$= 58 degrees, c′= 0 and $\gamma = 23 kN/m^3$ (Dusseault 1976)

The Pg_2 till is included with the glacio lacustrine deposits because it is only a few metres thick on the landslide site. It is conservative to ignore the till because it is stronger than the glacio-lacustrine deposits (Table 4.2.3a). The glacial sediments are considered to be fully softened (c′=0).

Figure 6.4 shows that most of the length of the surface of rupture is in the Clearwater sediments. The strength properties of the glacial deposits are kept constant and the cohesion in the Clearwater was reduced to achieve a factor of safety near unity. The c′ value in the Clearwater was initially set at 60 kPa, yielding a factor of safety of 1.4. At a factor of safety of unity, c′ is 15 kPa. The c′ value is reduced to simulate the process of softening.

Skempton and Hutchinson (1969, p.334) related the infinite slope analysis to "a series of curved but interlocking slip surfaces rather than a continuous planar shear." The ultimate angle (β_u) should be slightly steeper than the traditional ultimate angle value, 0.5 $\varnothing_r'$. Therefore, the retrogressive shallow earth-slide earth-flow movements in the glacial sediments are analyzed using infinite-slope analysis, although the factor of safety will be conservative. If the slope is fully saturated with flow parallel to the ground surface, the expression for the factor of safety is (Craig 1984):

$$F = \gamma' \tan \varnothing' / \gamma_{sat} \tan \beta \qquad (6.1)$$

Where: $\gamma' = \gamma_{sat} - \gamma_{water}$

The glacio-lacustrine sediments below the main scarp of the slide currently stand at 18 degrees and have a $\varnothing_r'$ of 24 degrees. The factor of safety is 0.7 if the slope is fully saturated. In reality, the slope is never fully saturated with flow parallel to the slope, but during peak rain events the water penetrates the weathered soil at the surface causing shallow flows. The slope in the glacio-lacustrine sediments should stand at 13 degrees to have a factor of safety of unity. The actual angle is probably 14 to 15 degrees, if the conservative nature of simplifying the retrogressive shallow earth-slide earth-flows to a planar slide is considered.

The glacio-lacustrine sediments in the crown of the landslide have cohesion because they form vertical scarps. Only fully softened sediments have a c′ of zero. The material moves after it has been softened by frost penetration which is assisted by the removal of the vegetative cover. As the slope angle decreases, the vegetation re-establishes itself providing enough cohesion to prevent shallow movements in the slope. The infinite slope analysis is used to model this process because planar movements are an approximation of the process described in this paragraph.

6.5 Discussion

I believe that as the crown of Slide 23-806c retrogressed there was a gradual transition in the mode of movement from rotational earth-slide earth-flows to shallow earth-slide earth-flows. The change in the mode of movement is caused by the overall angle of the slope being decreased as the main scarp of each preceding slide becomes shorter.

The profile of Slide 23-806c in 1995 is similar to the profile of Slide 23-806e in 1953. Therefore, I believe that vegetation will start growing on the colluvium of Slide 23-806c in the next few years. There was approximately ten years of growth on the colluvium of Slide 23-806e in 1953. Slide 23-806c was dormant in 1972. Therefore, it took about 30 years for Slide 23-806e to become dormant from a state of activity similar to Slide 23-806c in 1995. Slide 23-806c has been moving for 22 years, therefore I estimate that the retrogressive rotational earth-slide earth-flows are active for about 50 years before movements stop and the landslide becomes dormant.

Hutchinson (1988, p.14) stated that "an essential feature" of earth-slide earth-flows "is that the material involved has a metastable, loose or high porosity structure." Loose cohesionless materials, loess and high porosity weak rocks were the materials Hutchinson (1988) believed were involved in earth-slide earth-flows. The soil involved in sliding has some cohesion, is stable and has a low porosity. This is contrary to the statements Hutchinson made, but Slide 23-806c has a travel angle of 20 degrees and a volume of 5 x $10^4 m^3$ which fits into envelope for chalk flows shown in Hutchinson's Figure 12 (1988, p.15).

6.6 Conclusions

Slide 23-806c is an active, rapid to very rapid, retrogressive rotational earth-slide earth-flow in the Kcw and glacial sediments above the McMurray Formation oil sands. The majority of material was displaced between 1972 and 1981. Between 1981 and 1991, there have been more earth-slide earth-flows. The slides are probably triggered by a change in the flow of seepage toward Slide 23-806e to toward Slide 23-806c and a loss of strength caused by softening. The crown of the landslide has retreated about 60m at an average rate of 3m/yr displacing approximately 5.0 x $10^4 m^3$ of earth.

As the crown retreats, the style of movement has changed from rotational earth-slide earth-flows to shallow earth-slide earth-flows. Most of the movements are now in the glacial sediments that are approaching their ultimate angle of about 11 degrees. The strength properties of the Kcw and glacial sediments are estimated as $\varnothing' = 30$ degrees and $c' = 15$ kPa and $\varnothing' = 24$ degrees and $c' = 0$, respectively. The retrogressive rotational earth-slide earth-flows are active for approximately 50 years before movements stop and the landslide becomes dormant.

Chapter 7 Slide 11-376b

7.1 Introduction

Slide 11-376b is located at km 75 of the MacKay River and access is by foot from the AOSTRA road bridge that crosses the river at km 74.5.

Chapter 7 is divided into the following sections: 7.2) Air photograph interpretation, 7.3) Field investigations, 7.4) Literature review, 7.5) Stability analysis, 7.6) Discussion and 7.7) Conclusions. The field investigations section is further divided into the following sections: 7.3.1) Field observations, 7.3.2) Groundwater conditions, 7.3.3) Soil sampling and 7.3.4) Slide profiles.

7.2 Air photograph interpretation

Four sets of air photographs are discussed in this section. They are summarized in Table 7.2. The air photographs were obtained from Alberta Photo Services (Maps Alberta), Western Photogrammetry and North West Survey Corporation International Limited. There are fewer air photographs of the area surrounding Slide 11-376b because it is further away from Fort MacKay and the Syncrude Mine site than any of the other landslides. Figure 7.2a is a photograph of Slide 11-376b taken from an airplane on May 8, 1995 of Syncrude Research. Figure 7.2b shows the area surrounding Slide 11-376b on an overlay of air photograph 11-378.

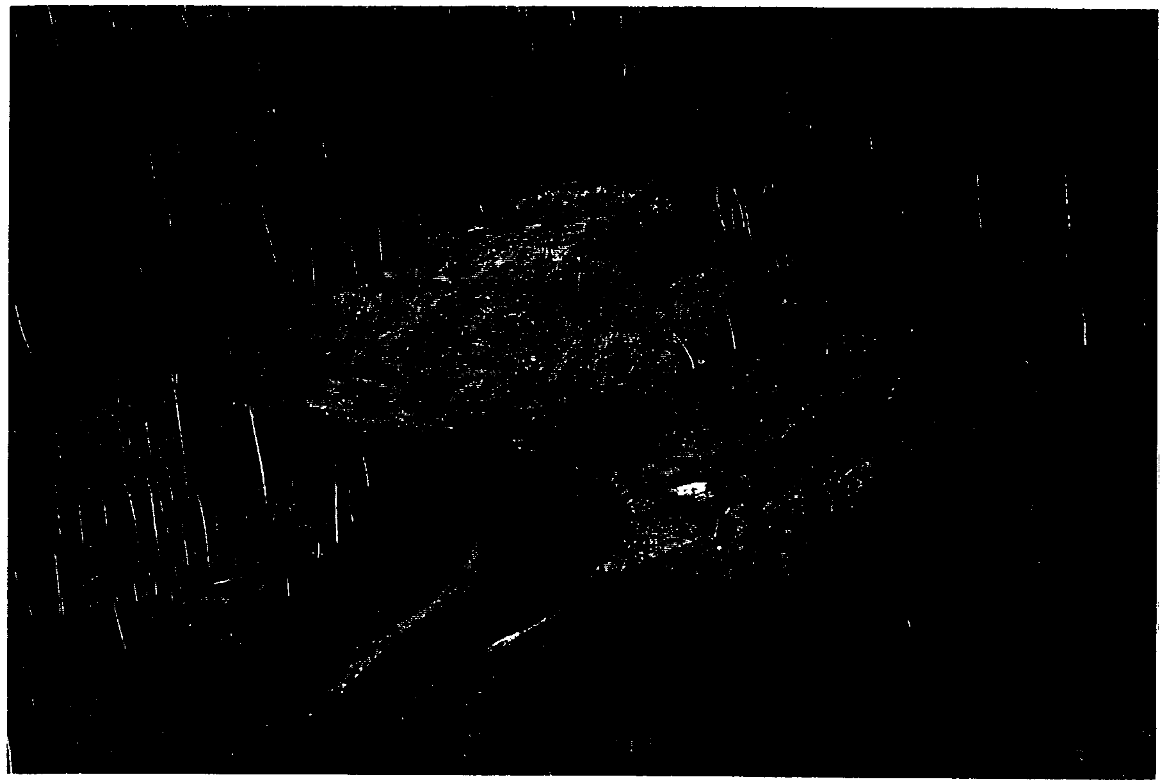


Figure 7.2a. Photograph of Slide 11-376b taken from an airplane on May 8, 1995.
The river is 50m wide in the centre of the photograph for scale.

Legend:

- Rounded break in slope, concave
- Rounded break in slope, convex
- Sharp break in slope, concave
- Sharp break in slope, convex
- Rounded scarp
- 10 Slope in degrees
- River terrace
- Landslide
- Marsh
- Wet ground
- Boundary of logging
- Drainage direction

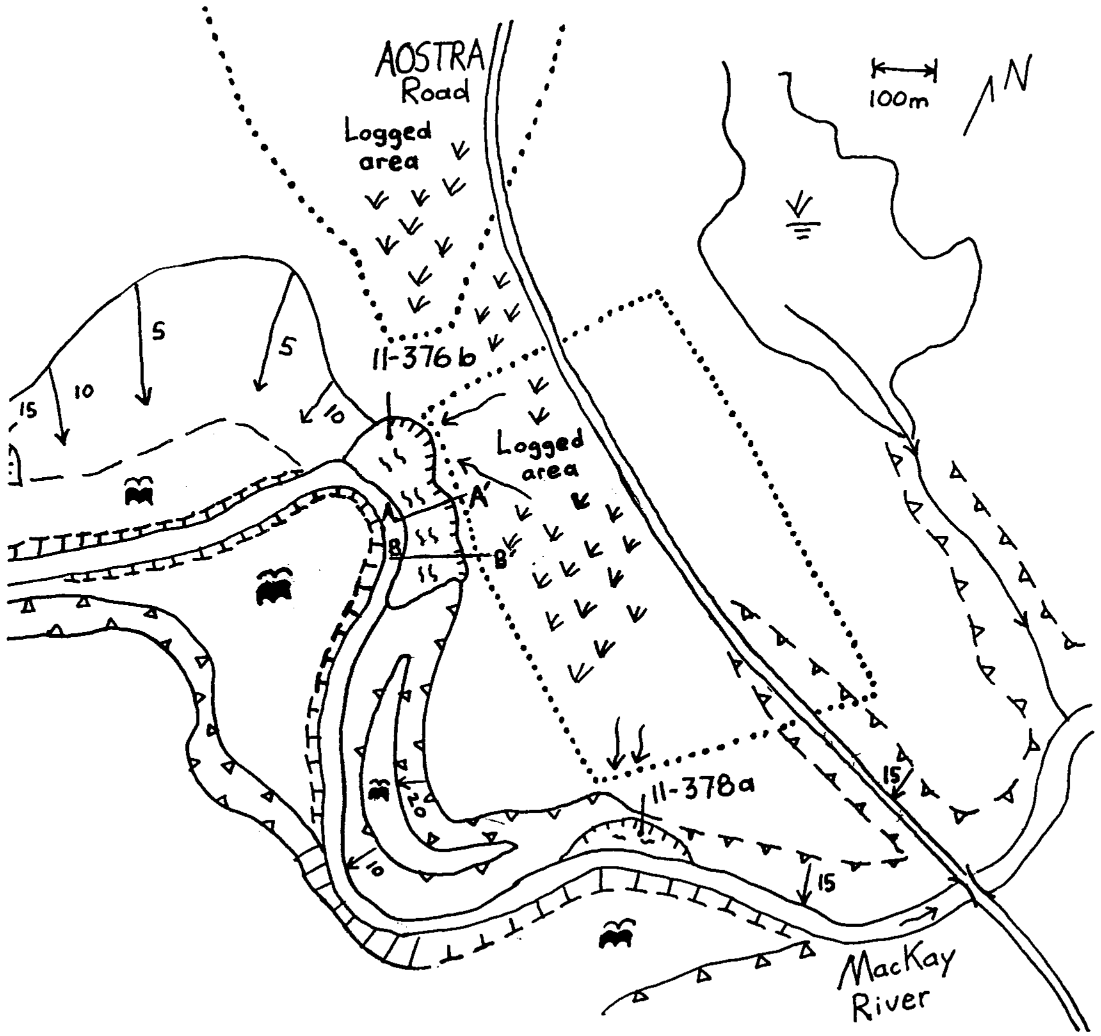


Figure 7.2b. Overlay of air photograph WP-9117-11-378.

Table 7.2 Air photographs of Slide 11-376b.

Identification number	Date	Scale	Source
AS 964 14	1967 08 31	1:31 680	Maps Alberta
AS 1201 187 (infrared)	1972 08 22	1:21 120	Maps Alberta
NW68881	1981 08 07	1:60 000	North West
WP-9117-11-376	1991 10 18	1:10 000	Western

On the 1967 air photographs there is no logging in the area and there is muskeg to the northwest and northeast of the top scarp of the landslide. There is a group of trees, approximately 4 to 6 metres tall, growing in the centre of the toe of Slide 11-376b. The trees are present in all the air photographs discussed in this section and were found during field investigations indicating that there have been no major movements in the centre of the landslide. The river channel beneath the downstream flank of the landslide is pinched from 40 to 20m in width showing that there have been recent movements. The section of narrow channel is approximately 50m long.

Figure 7.2b shows that Slide 11-376b is located on a slope that faces south. South-facing slopes get more sunshine in the northern hemisphere, therefore it is probable that the colluvium on the slide goes through more freeze-thaw cycles and weather quicker than non-south-facing slopes. The site of Slide 11-376b is very susceptible to freeze-thaw and penetration of frost because the vegetation mat is removed. It is possible there is a deep penetration of frost on the exposed slopes that leads to thin thaw flows in the spring. The fine-grained soils covering the slide site absorb a lot of water when they freeze then as they thaw the water cannot infiltrate resulting in increased pore water pressures.

On the 1972 air photographs there is no change in drainage and there is no logging activity. The river channel at the downstream toe of the slide is still narrowed to 20m, but the narrowed zone of channel has increased to 70m in length.

Between 1972 and 1981 there has been extensive logging around Slide 11-376b. A 200m strip of trees 40m behind the top scarp of the landslide, a 300m by 1000m area of trees to the northeast of the landslide and the large swamp to the northwest of the landslide have been logged (refer to Figure 7.2b for the exact locations of the logged areas). On the 1981 air photographs there appears to be no change in width of the narrowed channel near the downstream flank of the landslide, indicating that the rate of deposition of colluvium and the rate of erosion of the river are nearly identical. The colluvium from an earth-slide earth-flow has reduced the width of the river channel to 25m from 50m near the upstream flank of the landslide. The zone of accumulation forms a fan that is 70m long when measured across the original shoreline. The colluvium comes from the slopes near the upstream flank of the landslide. The scarp near the upstream flank has retreated faster than the remainder of the scarp indicating that surface flows of water have been increased in this area after logging operations. The total retreat of the upstream scarp is approximately 35m. Two-thirds of the retreat was probably caused during the large earth-slide earth-flow that deposited the zone of accumulation and the remaining third was probably caused by smaller retrogressive shallow earth-slide earth-flows in the glacial sediments. The logging activities, to the northeast, appear to have triggered Slide 11-378a that is visible on the 1981 air photographs, but not on the 1972 air photographs.

On the 1991 air photographs the vegetation appears to be recovering in the logged areas and the river has eroded most of the sediments deposited by the earth-slide earth-flow near the downstream flank of the landslide. A zone of accumulation approximately 60m long is still present below the upstream flank of the landslide. Figure 7.3a and b show the upstream flank of the landslide and the bend in the river where the zone of accumulation was eroded away. Colluvium in the upstream zone of accumulation was eroded at an average rate of 2.5m/yr (25m over 10 years). The landslide has little vegetation (except for the group of trees discussed earlier) growing on it indicating that there are small movements throughout the sliding masses preventing large trees and other plants from growing. The vegetation on the landslide in 1991 appears to be much less than in 1995. It is possible that the logging activities in the area increased the frequency of movements the slopes of Slide 11-376b and the frequency of movements is now slowing as the vegetation behind the scarps recovers. The AOSTRA Road has been constructed. The highway cut and drainage ditches excavated for the roadway should re-route some of the surface drainage and possibly reduce the frequency of movements on Slides 11-376b and 11-378a.

7.3 Field investigations

7.3.1 Field observations

The first observation is the difference in strength between the weathered saturated colluvium and weathered dry colluvium. The wet colluvium is extremely soft and difficult to walk on. Several days after the rain has stopped and the sun has dried the colluvium, there is no problem walking on the material. The weathering is caused by a combination of freeze-thaw cycles, wetting and drying cycles, surface drainage and seepage.

There is a shelf at approximately 20 to 23m above the river level that extends the entire width of the landslide. The shelf tops a layer of indurated siltstone, approximately 20cm thick, that protects the slope below (refer to Figure 7.3.4a). There are two successive shallow retrogressive earth-slide earth-flows in the glacial sediments above the break in slope and in the Clearwater Formation below the break in slope. The depth of both movements appears to be limited to the first few metres of weathered soil on the slope. Another mode of movement is blocks of colluvium held together by tree roots sliding downslope. Figure 7.3.1a is a photograph of a shallow earth-slide earth-flow in the material below the shelf. Figure 7.3.1b is a photograph of a block of colluvium sliding downslope. Both photographs were taken on June 29, 1995. The outside bend in the channel at the toe of the landslide is armoured with cobble-sized and boulder-sized blocks of siltstone left behind as the colluvium derived from the Clearwater Formation was eroded. The finer colluvium has been washed away, but the blocks of siltstone remain helping to amour the toe.

7.3.2 Groundwater conditions

Seepage from the face of the Clearwater sediments is shown by the salt deposits on the main slope. The colluvium at the landslide site has many rills and small gullies for surficial drainage to small swampy areas at the base of the slopes, near river level. It was raining during the first field visit to the site and there were many small streams on the landslide. Three days after the rain had ended the site was re-visited and there was no running water on the landslide.

The area north of the main scarp of the landslide is muskeg. Between the main scarp and the muskeg is a 40 to 70m zone of dry land that has poplar and spruce trees. Logging operations have removed the trees in the muskeg to the north and the marsh to the northwest. The wet ground near the crown of the landslide indicates that the water table should be assumed to be at ground level.

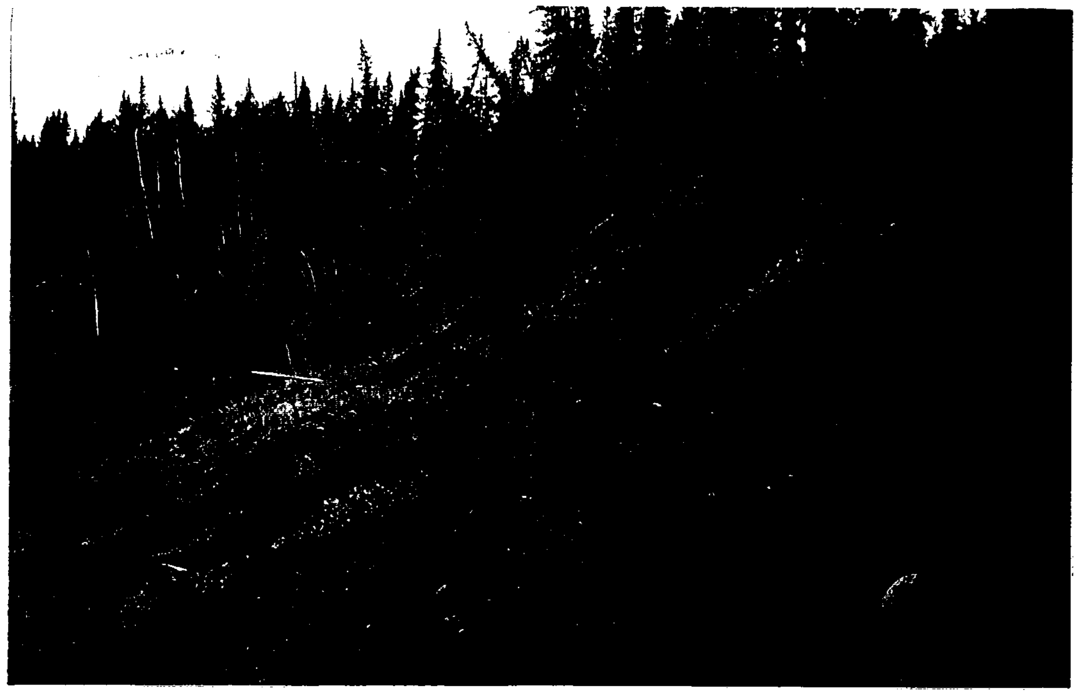


Figure 7.3.1a. Photograph of the slope below the shelf. Colluvium deposited by shallow earth-slide earth-flows in weathered Clearwater Formation bedrock is at the base of the slope. The tree in the middle of the photo is 2m high for scale

Figure 7.3.1b. photograph of a block of root-reinforced colluvium sliding on weathered glacial sediments. The head of the shovel at the bottom of the picture is for scale.