**University of Alberta**

# Landslides along the North Saskatchewan River in Northeastern Edmonton, Alberta

By

Pedram Zabeti ©

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

Department of Earth and Atmospheric Sciences

Edmonton, Alberta

Fall 1998

0-612-34441-X

## Library Release Form

**Name of Author:** Pedram Zabeti

**Title of Thesis:** Landslides along the North Saskatchewan River in Northeastern Edmonton, Alberta

**Degree:** Master of Science

**Year this Degree Granted:** 1998



Permanent Address:

Pedram Zabeti
314, 11012-82 Ave.,
Edmonton, AB.,
Canada, T6G 2P6

Dated: Aug. 24, 1998

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled *Analysis of Landslide Succession along North Saskatchewan River, Edmonton, Canada submitted* by *Pedram Zabeti* in partial fulfillment of the requirements for the degree of *Master of Science*

Dr. D.M. Cruden (Supervisor)

Dr. R.B. Rains (Committee Chair)

Prof. A.E. Peterson (Committee member)

Dr. S. Thomson (Committee member)

Date: June. 31, 1998

## ABSTRACT

This research analyzes the Lesueur and Oldman landslide successions located on the right bank of the North Saskatchewan River in northeast Edmonton. This research reports four main studies of them.

The first study examines the effects of landuse changes on triggering the slope movements through aerial photo interpretation, spanning 45 years. The second identifies the geological structure of the mass comprising both successions. Another study is the slope movement monitoring which has been carried out through different methods such as control surveying and mensuration. The final study consists of the ground surveys of the geometrical properties of 14 landslides (reactivated or inactive) for two purposes. The first one is to recognize the mode of sliding and style of activity. The other is to define the trend of post-movement deformation for the displaced mass.

The landuse study found that mining on the opposite river bank, and tree clearance in the upland area, have acted as triggering factors. The stratigraphic investigation found that in the upstream landslide succession, Lesueur, ice thrusting has occurred. This factor contributed to producing different types of landslides in the upstream and downstream successions. Mensuration and aerial photo interpretation, both used in slope movement monitoring, indicated that periodic river channel migration was responsible for reactivation of landslides during the past 35 years. Control surveying obtained the magnitude, trend and plunge of the movement vectors for different hubs set up at Lesueur landslide. Based on geometrical properties, the ground surveys divided the landslides into complex compound slides and multiple rotational slides. They also recorded the post-movement development of grabens and horsts.

*Summer of 98,*

***Dedicated to my mother who devoted her entire life***

***to me and many others….***

*Pedram*

# ACKNOWLEDGEMENTS

This research was carried out under the supervision of Dr. D. M. Cruden, Professor of Civil Engineering, at the University of Alberta. The author greatly appreciates his guidance, patience and encouragement throughout the course of study. Special thanks goes to Dr. S. Thomson who worked on the stability of this area for the past 35 years.

The author also wishes to thank Professor A. Peterson for his help with planning and performing the electronic distance measurements and for his technical advice. The author is grateful for the valuable comments and information provided by Professor R.B. Rains.

The cooperation of Mrs. L. M. Robertson is also appreciated who allowed access to her property on which the Lesueur landslide is located. The financial support of the research was provided through an NSERC grant to Dr. D.M. Cruden.

**Table of Contents** Page

**List of Tables** Page

**List of Figures** Page

# Chapter 1 INTRODUCTION

The Lesueur and Oldman landslide successions are located at the intersection of 33 St. N.E. and 137 Ave. N.E., Edmonton, Alberta. They include 14 landslides, reactivated or inactive, along their lengths. The largest is the Lesueur Landslide (1963) which is located in the upstream part of the Lesueur succession.

The focus of most previous studies, (Painter, 1965; Thomson, 1971; and Cruden et al., 1993) have been on the Lesueur landslide. The previous studies have considered the effects of the geological and hydrogeological processes as causal or triggering factors of the instability. However, this research also has undertaken a study of the landuse history to investigate the effect of human activities as a triggering factor (Secs. 2.3.3 and 5.3.3). As previous studies have determined the physical, mechanical and chemical properties of the materials comprising the slope at the Lesueur landslide, topics left for this research to investigate are as follows: identifying landuse changes and their effects on instabilities by aerial photo interpretation (Chapter 3), and determining the structural properties of the mass, which comprises the slopes, by a stratigraphic investigation (Chapter 4).

To monitor the slope movements, three approaches have been chosen. The control surveying (Sec. 5.1) obtains the magnitude and direction of the Lesueur landslide toe movement. Mensuration determines the interactions of the North Saskatchewan River and the landslides along the successions (Sec. 5.2). The third part of Chapter 5 describes aerial photo interpretation to find the spatial and temporal distribution of the slope movements.

In order to determine the deformation pattern of the slopes (their geometrical changes) and to define the types of the surfaces of rupture of the landslides, ground surveys have been carried out to provide the longitudinal profiles of the slopes (Chapter 6).

Chapter 7 gives the conclusions of this research. It includes the effects of the landuse changes on slope movements, the mechanism behind the reactivation period of the landslides and the deformation pattern. It also summarizes the activity status, movement type and mode of sliding for each landslide. These conclusions provide a better understanding of the landslide mechanism which in the future will lead to a more accurate behavioral prediction of those landslides that is needed for sustainable development.

# Chapter 2 PHYSICAL SETTING AND HISTORY

## 2.1 - INTRODUCTION

This chapter introduces a summary of the physical setting (Sec. 2.2), geological history (Sec. 2.3.1) and stress history (Sec. 2.3.2). Also, it includes the results of landuse history undertaken by this research (Sec. 2.3.3).

## 2.2 - PHYSICAL SETTING

The landslide successions are centered at section 27- 53 -23 -W4, on the outside of a bend of the North Saskatchewan River in northeast Edmonton, Alberta, Canada (Figs. 2.1, 2.2). The 2 km length of the meander consists of almost equal upstream and downstream segments divided by the Oldman Creek (Fig. 2.3). The upstream part of the succession is called the Lesueur succession and the downstream one, the Oldman succession. The number of slides comprising the Lesueur and Oldman successions are 8 and 6, respectively. The average horizontal distance between the slope crest and the river edge is 68 m along the Lesueur segment but decreases to 48 m along the Oldman segment. The slope crest elevation changes from 31 m above the river level to 28 m, moving from upstream of the Lesueur succession towards downstream of the Oldman succession. The overall slope angle ranges from 18 ° to 43°. The usual North Saskatchewan River width along the succession ranges from 150 to 200 m, presently.

The North Saskatchewan River is the main drainage channel of the area and the landslide succession is located where its meander extends eastwards and then northwards. Bounded by this part of the meander, there are two tributaries. They enter the North

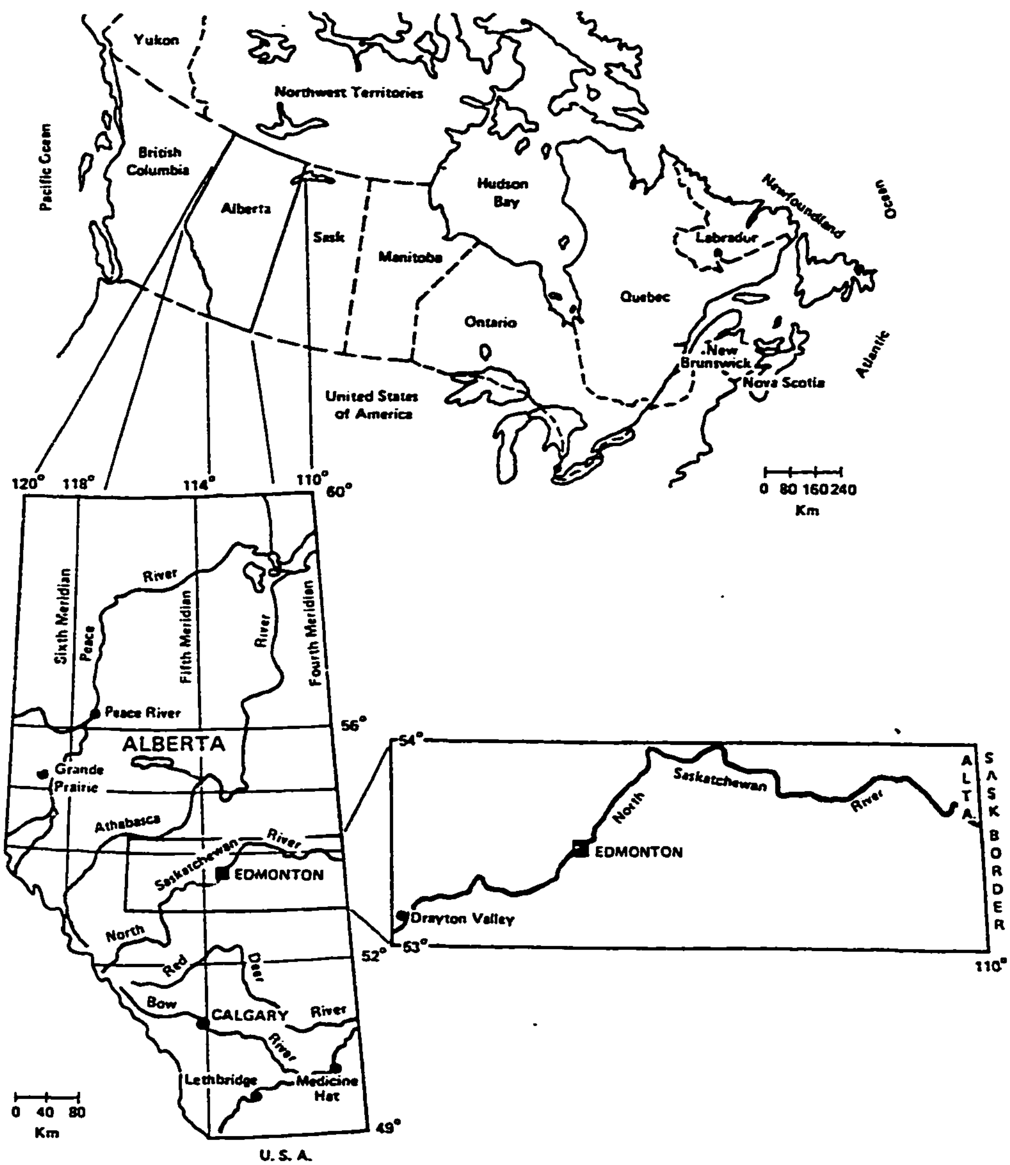
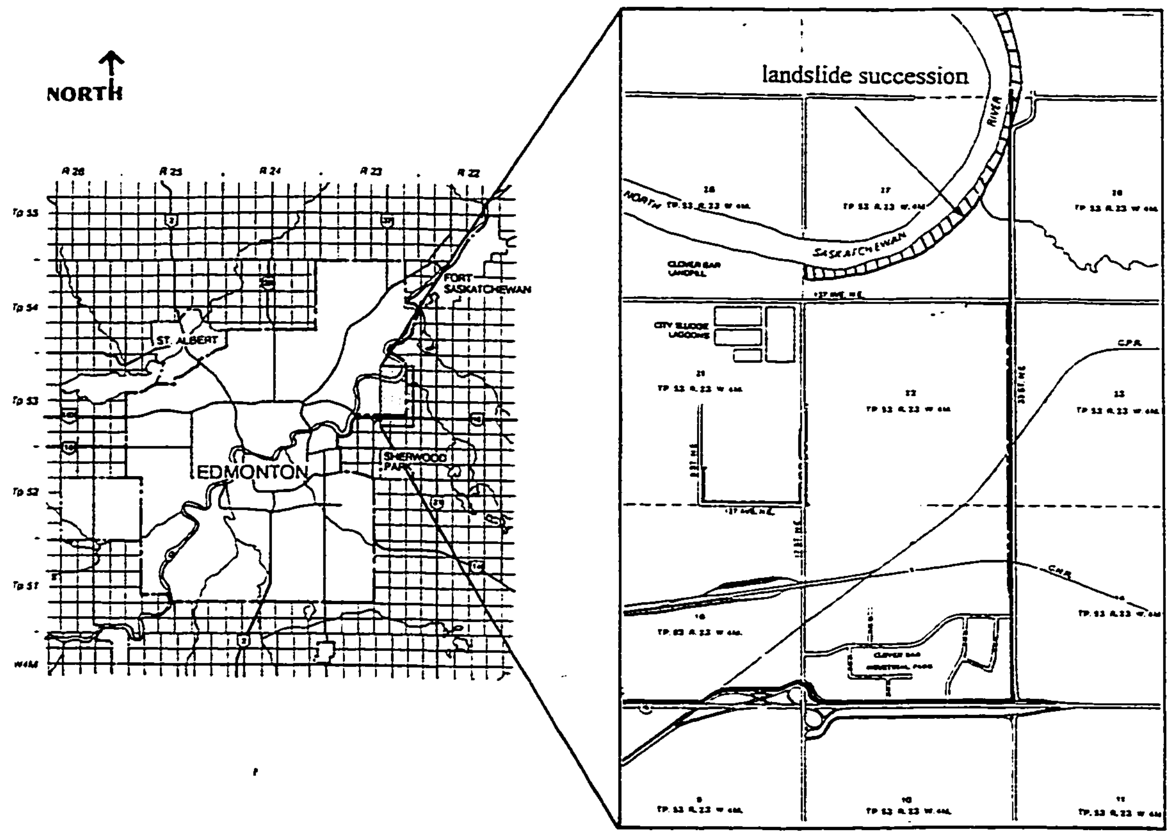



Fig. 2.1 - Location map of Edmonton, Alberta.




Scale – 1 / 65000

Fig. 2.2 - Location map of the landslide succession

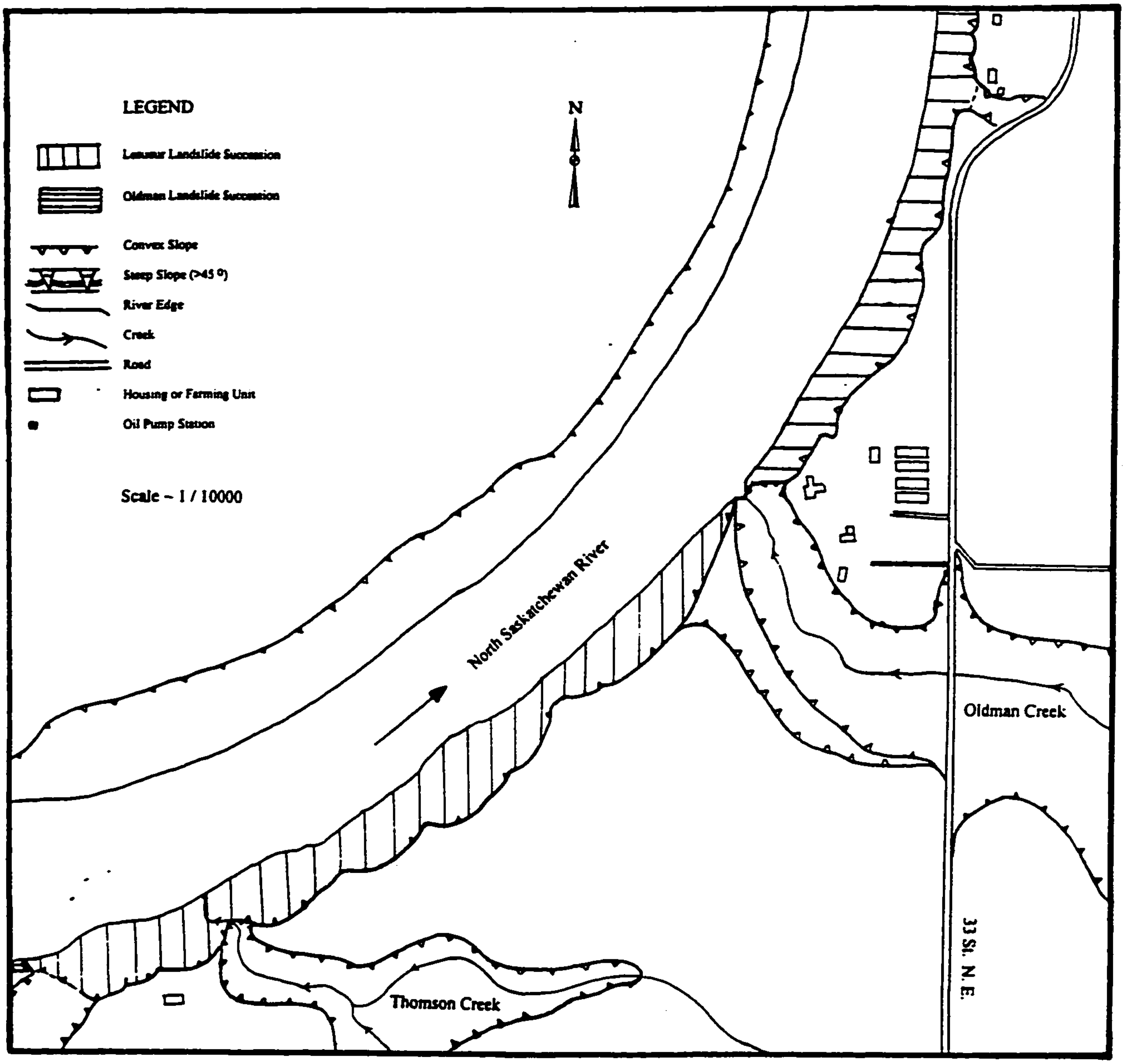



Fig. 2.3 - Map showing the Lesueur and Oldman landslide successions

Saskatchewan River from its south bank, approximately perpendicular to the river. It worth noting that the south and north banks are right and left banks, respectively. As the previous literature informally named those banks south and north, here they are called the same. One of the tributaries is thomson creek (informal name) and the other is Oldman Creek. Thomson creek extends for 850 m and Oldman Creek for more than 2200 m.

The drainage system in the upland area is deranged. The upland are

a, south of the landslides' scarps along the successions and even for the entire area, which stands at elevation of 640 m a.s.l., is level and slopes at less than 3 ° towards the river valley. The ground surface comprises of glaciolacustrine sediments.

The opposite side of the bend, the north bank, is cut into the lowermost terrace (T4) of the North Saskatchewan River standing about 7 m above river level. The north bank, stands at steep angles, having an unvegetated bank along the segment opposite the Lesueur landslide location.

The outside of the bend, the area of the landslide successions, is occupied by the same age terrace only from Loc. 6 upstream, (Figs. 2.4 and 2.5 for the map of the locations). The upland elevation at this part of the outside of the bend drops 25 m, from 641 m to 616 m. The radiocarbon dating by Rains and Welsh and others (1988) found the age of 8500 years B.P. for the low level terrace (floodplain). It is evident from the aerial photos in Appendix B that this terrace does not exist at the outside of the bend, along the landslide succession.

Kathol and McPherson (1975) reported that the area has a climate described as continental, varying between dry and moist. It has a subhumid warm summer and a long cold winter, which lasts about 5 months starting in early November till the end of March.

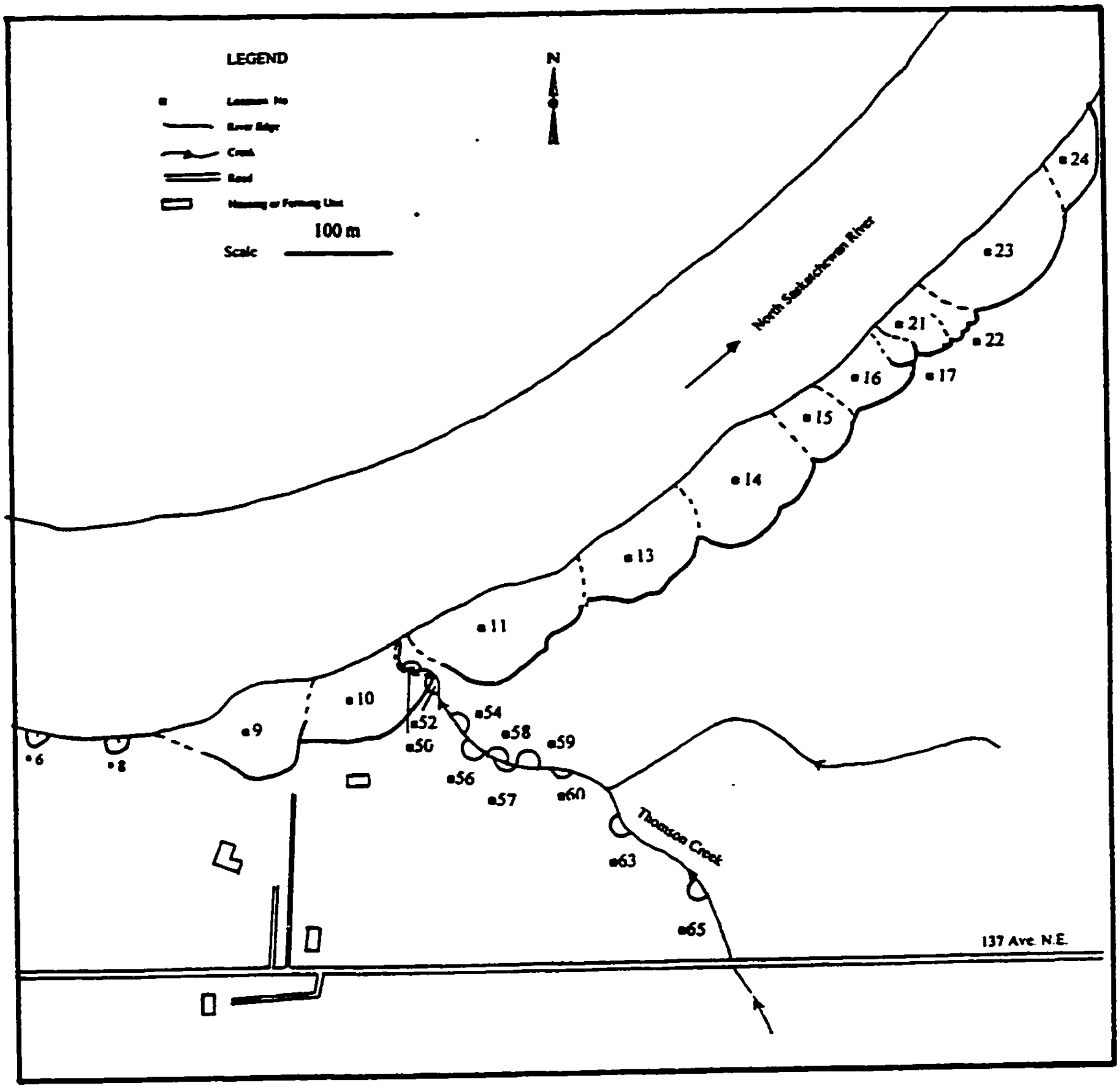



Fig. 2.4 -Location map for the landuse history study, stratigraphic investigations, aerial photo interpretation, mensuration and ground surveys carried out along Lesueur succession. Loc 0 is located 60m (10mm) to the west of the west margin of the map. Figure is an overlay of the aerial photo.

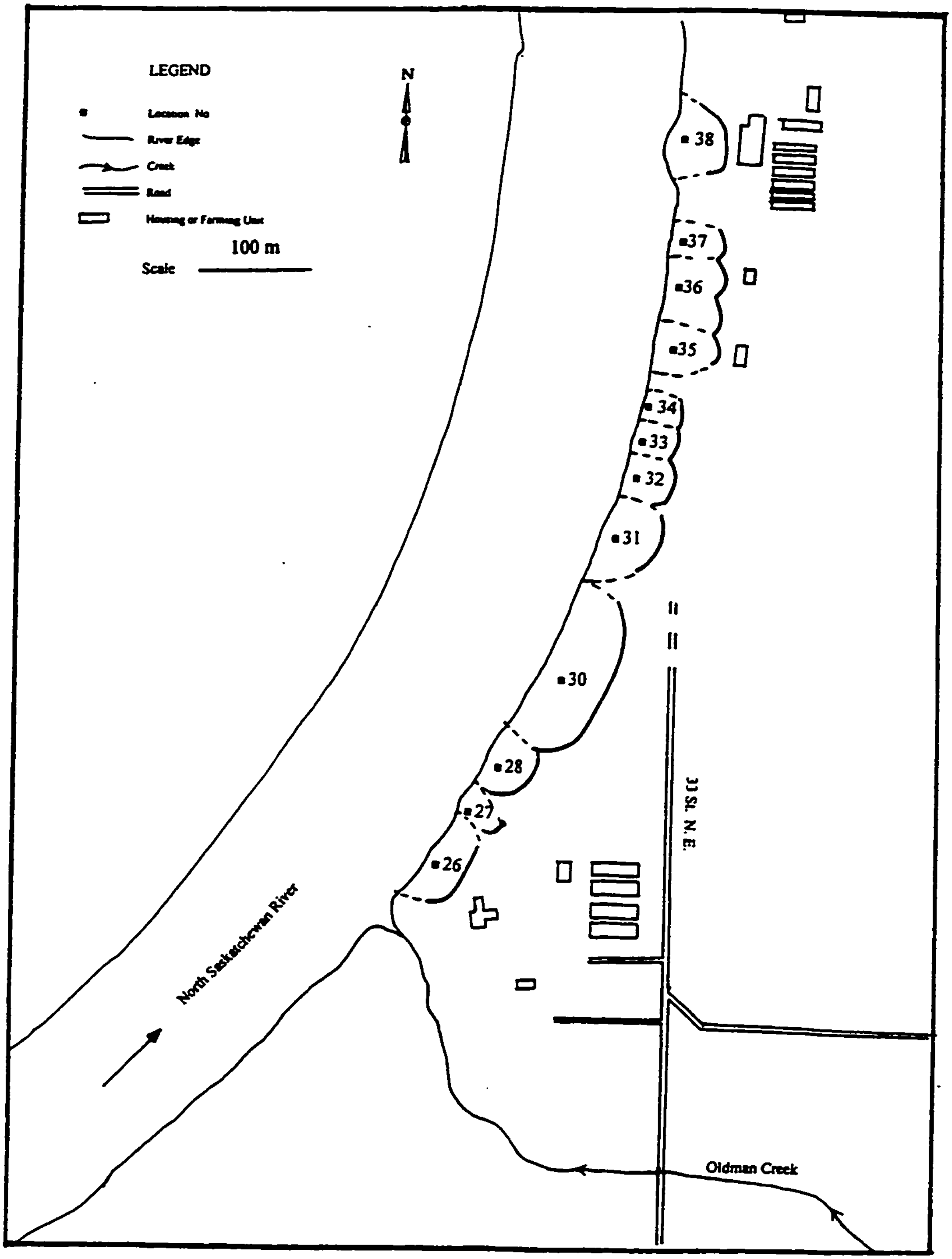



Fig. 2.5 -Location map for the landuse history study, stratigraphic investigations, aerial photointerpretation, mensuration and ground surveys carried out along Oldman succession. Figure is an overlay of the aerial photo.

The difference in mean temperature between the warmest season and the coldest for the area is 33$^{o}$ c. The average frost-free period for Edmonton is 100 days varying from 50 to 150 days. On the average, the first frost occurs during the first week of September and the last one during the last week of May. The yearly mean wind speed is 15 km/h, which is one of the lowest on the Prairies. The predominant wind direction alternates between south and northwest. As this location is outside of the city, the wind is unimpeded by building and can gust to over 130 km/h.

The wind chill decreases the mean temperature in January from -14 to -31 $^{o}$ c (EMR Canada, Temperature Map,1985). The precipitation is moderate during all seasons. Total precipitation averages 470 mm per year of which 350 mm falls as rain and 120 mm as snow (EMR Canada, Precipitation Map, 1991).

Thunderstorms are common and are responsible for much of the rainfall during June, July and August. June and July are the wet months of the year. Rainfalls of up to 130 mm per day and snowfall of 380 mm per day may occur (Kathol and McPherson, 1975).

## 2.3 - HISTORY

### 2.3.1 - GEOLOGICAL HISTORY

Investigations have recently been conducted into the geology of the Edmonton area by Andriashek et al. (1997), Kathol and McPherson (1975), Rains and Welsh (1988). Godfrey (1993) described the geological history of Edmonton which is summarized in the next paragraph. It worth noting that the geology of Edmonton area has been investigated by E.J.W. Irish primarily. More information regarding the surficial geology of Edmonton was introduced by Bayrock and Hughes (1962) and Bayrock and Hughes (1966).

The oldest exposed rocks are Late Cretaceous, and named Horseshoe Canyon Formation. They have been mainly exploited for coal. The processes that led to the coal seams are as follows. In early Mesozoic time (about 225 My B.P.), Alberta formed the western shoreline of the North American continent. The sea had withdrawn from the land mass to lie in the western part of the Province. The rivers fed the coastal water with abundant clay, silt and sand, which resulted in developing deltas and mud banks along the coast. As a result of poor drainage, vegetation flourished in swamps. Their subsequent rotting led to abundant decaying plant debris, which produced the coal layers in the southern part of Alberta and British Columbia. In the late Mesozoic, Cretaceous Period (~136 My B.P.), an offshore range of volcanic mountains rose to form a barrier off the western coast. Thus, the sediments flowed to the Alberta sea from the Cordillera to the west and from the Canadian shield to the northeast.

As a result of the collision between the Pacific oceanic crust and the continental crust of the North America, the Rocky Mountains were built. Great clouds of volcanic ash were blown inland over the Edmonton region. Therefore, many of the inland deltas and swamps were choked with ash. This situation is visible in many of the Cretaceous strata of the Edmonton region. They do not look like ashes as, through time, the weathering has decomposed them into a sticky, clay-rich soil known as bentonite. In the Late Cretaceous, existence of suitable conditions such as abundant fertilizing volcanics, cooler temperatures but still a Mediterranean climate and abundant rainfall led to flourishing vegetation. The subsequent large volumes of the rotting organic materials, produced coal layers in central Alberta. Also, some part of this organic mass was converted to the oil and gas which were trapped in porous sandstone. At the end of the Cretaceous Period, the thick blanket of debris converted to conglomerate, sandstone, siltstone and clayey or silty shale.

During the Cenozoic Era (that began 65 My ago), the Rocky Mountains were still being thrust into the western sector of Alberta. It was during this Era that most of the present topography developed. As the mountains rose, they have been removed by subaerial erosion. It has been reported by Norkowski (1984) that subaerial erosion has removed approximately 700 m of clastic sedimentary rocks, formerly deposited during the late Mesozoic.

The area has been affected only by the last advance of the ice sheet, the Wisconsin stage starting 0.02 My (21000 y) B.P. As the area was far from the centre of the ice sheet, the plains were covered by up to 1.5 km of ice which flowed from northeast and north.

Glaciation has substantially modified the preglacial bedrock surface in the Edmonton area. The Wisconsin advance of ice sheet from the NE was responsible for both erosional and depositional processes. The erosional ones resulted in partial or complete removal of the preglacial sediments and modification of the bedrock surface.

The modification of the bedrock surface ranged from a scour of a few metres into the bedrock surface to the thrusting of huge slabs that were tens of metres thick. Glacial forces on the edge of the preglacial river banks have also thrust large bedrock slabs long distances from their original positions. The material incorporated in the ice was then deposited primarily as glacial till that ranges from a few metres to more than fifteen metres in thickness in the Edmonton area. The City of Edmonton (1990) reported the till is usually clayey (referred to as clay till) but far from homogeneous material as preglacial sediments, thrust bedrock and glaciofluvial sediments are parts of the structure.

Subsequent to the last glaciation, surface drainage was prevented from flowing north due to ice dams. Glacial Lake Edmonton covered the region and the glaciolacustrine sediments were deposited over a broad area. The deposits are relatively thin in northeast Edmonton, which includes the landslide succession area.

The Wisconsin glacier began to clear the Edmonton region about 12000 years ago. Glaciofluvial processes have played an important role in the drastic modification of the landscape. Because of the huge volume of this ice melt and subsequent land rebound as a result of glacial isostasy, the river downcutting rate increased. The process of fast river downcutting has led to a rapid erosion of material.

As Rains and Welsh (1988) stated, the most significant postglacial activity in this area was the river incision by the North Saskatchewan River after drainage of Glacial Lake Edmonton. At first, river down cutting predominated over lateral erosion to produce 3 terraces about 3000 years, from 11500 to 8500 years ago. Since that time the T-4, floodplain, has been formed by a series of overbank flood events. These terraces have been radiocarbon dated by Rains and Welsh (1988) by radiocarbon dating. The T1 is the oldest and highest one, 55 m above the river level and T4, floodplain, is the youngest and lowest one, 7 m above the rive level and formed from 8500 years ago to present. Since 8500 years ago, the river down-cutting has been very slow, showing that the river has worked, and is presently working, sideways and undercutting its valley walls causing instability. The rate of river down-cutting over last 8500 years at Edmonton has been estimated by Rains as 0.025 m / 100 years (see Fig. 2.2 in Cruden et al., 1993)

### 2.3.2- STRESS HISTORY

Two processes independently and at different times have played important roles in unloading the bedrock and or surficial materials. The first was the preglacial subaerial erosion that happened during the Tertiary Period which has removed about 700 m of the overlying materials and has led to the relaxation of the bedrock (Bayrock and Hughes, 1962).

The latest phenomenon in the area that has also played an important role in unloading was deglaciation. The last phase of glaciation, the Wisconsin (ended about 12000 years B.P. ) has affected this area (Bayrock and Hughes, 1962). During glaciation as a result of high compressive forces at the base of the moving ice sheet, the bedrock experienced extremely high shear stress and was disturbed so that large slabs of it have been separated and displaced by ice. Kathol and McPherson (1975) and the City of Edmonton (1990) report on hydrogeologic assessment have stated that the slabs of bedrock were intersected within the glacial sediments at approximately 20 % of the testholes drilled for their projects.

As a result of rapid downcutting of the North Saskatchewan River the land has been uplifted as the tremendous loads of ice have been removed. Consequently, the valley rebound has led to a localized upward-bending of the bedrock layers at the valley floor (Matheson and Thomson, 1973).

#### 2.3.3- LANDUSE HISTORY

The study of the landuse history for the area has been carried out by reviewing the existing maps and by interpreting the aerial photos. The upland area of the Lesueur landslide has been extensively used for agricultural purposes, which goes back prior to 1971. The farming activities have increased by 4% from 1971 to 1976 (Energy, Mines and Resources Canada, Farm Operator Map,1985).

The landslide successions, Fig. 2.3, are situated in the area with the following characteristics. The area has been graded as priority 1 class, which requires normal conservation with crop use. More than 80% of this zone has been cultivated having moderate or no significant limitations for dryland agriculture. They are highly productive for a wide range of field crops. The soil can be managed and cropped without difficulty (Alberta Agriculture, Provincial Base Map,1983).

The study area was classified as grassland, which has been invaded partially by woodlands, mainly deciduous trees. Droughts are rare and it is the most fertile soil zone in the province (Agriculture Canada, Soil Survey of Edmonton, 1962).

Another major human contribution to the environmental changes is the oil pipeline construction, upstream of the study area, by the Rainbow Oil Pipeline Co. Ltd.

This pipeline passes by the upstream boundary of the landslide succession area and extends towards the northwest.

The study area has also been exploited by two gravel pits adjacent to the landslide successions. One is located on the north bank terrace, and another one, which is larger, on the south bank but upstream of Loc.6. Their properties are shown by Table 2.1 taken from Alberta Geological Survey map (1981).

Table 2.1- Properties of the gravel pit activity on the south and north banks

| *Location* | *Material* | *Reserves ( m3)* | *Remarks* | *Overburden Thickness (m)* | *Deposit Thickness (m)* | *Deposit Area ( m2)* | *Deposit Genesis* |
|---|---|---|---|---|---|---|---|
| South Bank | clean to dirty sand and gravel | 14.2 x 10^ 6 | upper level sand, lower one sandy gravel and gravelly sand | 1 | 8 | 550 | Fluvial terrace |
| North Bank | clean gravelly sand | 11.8 x 10 ^ 6 | | 2.5 | 4.0 | 440 | Fluvial terrace |

In order to study the landslide successions either by aerial photo interpretation or field investigation (stratigraphic and ground surveys), the landslide successions have been divided into locations mapped in Figs. 2.4 and 2.5.

The following is a list of landuse changes that the landslide successions area has experienced from 1952 to1997. Details of the aerial photographs are given in Table 1, Appendix A.

1952-1962

Photo No. 2:

-As a result of mining activity (on the north side of the riverbed, a pit with dimension of 180 m x 15 m has been excavated and a pile of wastes with dimension of 600 m x 20 m has been dumped upstream of the pit, on the north side (shore) of the river. It was not possible to identify either the mining activity was alluvial gold mining or gravel mining. This location is exactly opposite the Lesueur landslide, Loc. 9,

- Trees around the old Lesueur house, Loc. 9, have been cleared,
- North bank has been in use for agricultural purposes,
- There is a septic tank 35m to the east of the old Lesueur house, Loc. 9,
- Some industrial units have been added at 137 Ave. N.E., where it is 230 m to the south of the old Lesueur house, Loc. 9.

1962-1971

Photo No. 3:

- The oil pipeline construction was undertaken by the Rainbow Co. Ltd. Consequently, the slopes of the south and north banks upstream of the Lesueur landslide, Loc.9, have been cleared of trees and instead of that colluvium covered the slopes. This pipeline is about 210 m to the west of the western scarp of the main Lesueur landslide, Loc.9.
- A new house has been built 43 m to the east of the previous location of the collapsed Lesueur house, Loc. 9,
- Another new house has been built 62 m to the south of the house at the upland of the Loc.9 ,
- The septic tank of the old house has been removed, Loc. 9,
- Gravel pit mining activities have been started on the north bank terrace.

1971-1974

Photo No. 6:

- The gravel pit on the north bank terrace shows a substantial increase in its activity,

Photo No. 8:

- Along Oldman succession two industrial units have been developed: 1) animal farming unit at the upland area of Locs. 26 & 27, 2) greenhouse unit at the upland area of Loc.38. Also four tanks have been built to the east of Loc. 38.

1974- 1976

Photo No. 9:

- The gravel pit at the north bank has been leveled at the previously active zones, but activities have begun on the eastern part of that terrace,
- One barn has been added 150 m to the south of the western scarp of the Lesueur landslide, Loc. 9

Photo No. 11:

- Four tanks to the east of the Loc. 38 have been removed,
- Two depressions with the area of 150 x 150 m to the south of the Loc. 38 have been leveled and their discharge channels to the gully, to their west, have been disconnected.

1976-1980

Photo No. 12:

- Vegetation has started to develop at the north bank gravel pit, while gravel pit activities have been concentrated at the eastern part of the north bank terrace,

- An open lagoon unit with dimensions of 220 m x 400 m has been built 570 m to the west of the Lesueur landslide location, Loc. 9, for the Edmonton Waste Management System,

Photo No. 14:

- Another development stage of the farming unit at Loc. 26 & 27 and the greenhouse units at Loc. 38 is visible.

- Those leveled and filled depression areas to the southeast of the Loc. 38 started to subside again and produced depressions again,

- The Oldman Creek has been dammed upstream of its intersection with 33 St. N.E., which could be the result of a plugged culvert

1980-1982

Photo No. 15:

- Another phase of the north bank gravel pit development at the eastern part of the north bank terrace has taken place,

Photo No. 16:

- West and east slopes of the road embankment on the Oldman Creek have been cleared of trees,

Photo No. 17:

- The depressed area to the southeast of the Loc. 38 has subsided more and has been connected to the gully, to the west, by a drainage path.

1982-1984

Photo No. 18:

- The entire scarp of the Lesueur landslide, Loc. 9, has been trimmed of trees,

Photo No. 19:

- A drainage channel that collected the agricultural wastewater has been reshaped and deepened in the upstream part of Thomson creek and discharged those wastes to Thomson creek,

Photo No. 20:

- At Locs. 26 & 27, the depression (pond) between the animal farming unit and its valley escarpment, has been insulated by a liner in order to prevent water seepage from this upland area to the slope which previously experienced instability problems (as the owner of the farming unit mentioned),
- Again the two depressed areas, located to the southeast of the green house, and their connection to the slope have been removed.

1984-1986

Photo No. 21:

- A large power transmission line across the North Saskatchewan River, upstream of the landslide succession, west of Loc. 9, has been built,
- Gravel pit mining is still active.

Photo No. 23:

- Tree clearance at the southwest slope of the animal farming unit, Loc. 26, was undertaken in order to install a water pump for water supply and also for a wide passage as an access path to the North Saskatchewan River at river level.

1986-1988

Photo No. 24:

- The north bank gravel pit has experienced a dramatic development stage,

1988-1990

Photo No. 29:

- Oldman Creek has been dammed again, to the east of its intersection with 33 St. N.E.

1990-1993

Photo No. 30:

- The north bank gravel pit has been cultivated,

Photo No. 32:

- The industrial unit at Loc. 38 has had another stage of development.

1993-1995

Photo No. 33:

- One of the north bank pump stations of the oil pipeline has been enlarged

1995-1997

Photo No. 36:

- The north bank terrace has been used for the agricultural purposes,

Photo No. 37:

- The two depressions, to the southeast of the Loc. 38, again have been connected to the gully, to their west.

## 2.4 -CONCLUSIONS

The conclusions will be introduced at the end of Chapter 5 as these observations should be compared with the slope movement monitoring results in order to identify the effects of human activities on causing instabilities.

# Chapter 3 GEOLOGICAL SETTING

## 3.1 - INTRODUCTION

This chapter describes the site geology (Sec. 3.2), the distribution of the buried channels (Sec. 3.3), hydrogeology of the area (Sec.3.4) and finally the river channel topology (Sec.3.5). The site geology explains the kinds of geological materials that comprise the valley wall, from bottom to top: bedrock, preglacial sediments, glacial sediments, lake sediments, postglacial sediments and at last the soil. The hydrogeology section indicates the existing aquifers and their physical properties, the number of flow systems and the direction of the groundwater movements within the valley wall. Sec. 3.5 determines the differences in slopes of North Saskatchewan River channel walls.

## 3.2 - SITE GEOLOGY

The following site geology has been adapted from City of Edmonton (1990). It is worth noting that the surficial geology of Edmonton has been described by Bayrock and Hughes (1962) and Bayrock and Berg (1966).

The surficial deposits that cover the site are complex. However, the bedrock beneath them is much more uniform. The Horseshoe Canyon Formation makes up the bedrock. It is a brackish to fresh-water deposits that have been poorly consolidated . The bedrock layers dip gently to the southwest at approximately 0.28 °. The formation is predominantly clayey to silty shale, which grades locally to a sandy shale. The shale contains thin interbeds of sandstone, coal and bentonite. The silty shale is light gray while the clay shale is dark to light gray ranging from bentonitic to carbonaceous. The interbeds are not laterally continuous over long distances and display rapid changes over short intervals. The Horseshoe Canyon Formation is not extensively fractured but in the coal seams fracturing is expected. However, the existence of the mica (biotite) and carbonaceous matter enhances the fissility of the bedrock.

The sandstones are fine grained, bentonitic and often grade to siltstone, poorly cemented and weak. The coal seams are of variable quality and generally only 0.40 to 0.60 m in thickness. The Horseshoe Canyon Formation as encountered during the field investigations is not very hard, as auger refusal was not encountered in any testhole drilled for different projects.

The surficial deposits in the Edmonton area have been extensively investigated and were mapped in detail by Kathol and MacPherson (1975), and Andriashek (1988). The thickest deposits are typically associated with buried valleys where total thickness of 50 m or more are common. In places where deposits are thick, large horizontal and vertical variations are frequently observed. Tedder (1986) stated that the thickness of the surficial sediments varied from 30 m within the preglacial valleys to 5 m over the bedrock uplands.

The oldest surficial deposits form the Empress Formation which dates up to the late Wisconsin, 21000 y B.P., just before the last glaciation (Andriashek, 1988). This formation includes fluvial sands and gravel deposited by a braided river flowing in the preglacial valleys.

Painter (1965) reported that the sands are fine to coarse textured, light to grayish brown in color, and gravels particles are composed of quartzite and cherts with some arkose pebbles.

Thomson (1971) observed 6 m of the Empress Formation at the Lesueur area. Typically, it includes two parts, as a layer of sand overlies the lower sand layer, which is interbeded with gravel. Some layers are not bedded while the others are laminated. Tedder (1986) mentioned that they might even display coarse cross-bedding.

A till unit exists which is thicker where it infills the buried channels. Its thickness ranges between 3 and10 m. Wherever the preglacial sand and gravel of the Empress Formation exists, the till lies on it instead of the bedrock. The till has a medium to dark gray color in an unweathered state, as encountered during borehole samples, while in outcrops it is light to yellowish brown. The grain size within the till ranges from clay sizes to boulders, larger than 150 mm in diameter. The till forms near vertical faces that display rectangular or columnar jointing. Tedder (1986) reported the existence of numerous lenses and pockets of sand and silt throughout the till. Painter (1965) stated the till is clayey, 30-40 % clay, 30 % silt and 40% sand. The clay fraction usually contains a large percentage of montmorillonite. Textural analyses of 11 samples demonstrated a very narrow grain size variation, suggesting that the till was likely deposited as a single unit.

In some specific site investigations, such as the Edmonton Waste Management Centre project carried out by the City of Edmonton (1990), another unit, at the base of till, has been specified called the Thrust Shale-Lower Till. Ice thrusting has produced this unit and the act of shoving the bedrock shale has produced bedrock slabs observed in many locations during drillings of boreholes. The thrusted shale had a sand layer at its top as a result of the preglacial processes and also another sand layer at its base as these slabs have overridden the preglacial sand. In some locations its thickness was more than 10 m.

The lower till below the thrusted shale had a very high clay content and extremely high plasticity. It is worth noting that where the thrust block was underlain by this lower till or by preglacial sand and gravel, it was relatively simple to identify the boundary between the undisturbed bedrock and the thrusted bedrock. In some testholes, those layers were absent and the true bedrock contacts were identified by interpolation from adjacent testholes. In Kathol and McPherson (1975) and City of Edmonton (1990), it has been stated that approximately 20 % of the testholes drilled for their project, intersected the slabs of bedrock within the glacial sediments.

The uppermost surficial unit consists of lacustrine sediment. Its thickness varies from zero to 4 m. The lacustrine sediments are reasonably uniform with the exception of a 300 m wide band parallel to the slope crest. In this band, the lacustrine deposits are clay interbedded with silt, as the north margin of the Edmonton Glacial Lake has been identified just 1.5 km to the north of the Lesueur landslide location. Eight samples of the lacustrine deposits showed 40 to 60% clay. Painter (1965) found even sand in lacustrine deposits as the recent field investigations (1997) also showed the same situation. Tedder (1986) stated that the thickness could be up to 6 m and composition could vary from silty clay to clayey sand. It might even include ice rafted till layers (Andriashek et al., 1997). These lake sediments are dark gray in less weathered samples from boreholes and light gray in the outcrops. They have low to medium plasticity. The clay layers of the lacustrine deposits vary from being unbedded to laminated with thin layers of dark, highly-plastic clay and light silt (City of Edmonton,1990).

Alluvium found on the terraces, specially the lowermost (T4), consists of two parts. The usually thicker part that overlies the bedrock comprises sands and gravel. It is overlain by a thinner layer of silt and clay. Colluvium is also found in the area. Its thickness depends on the type and magnitude of the slope movement that the slope has experienced. Its thickness could range from 1 to 5 m where the slope has undergone block fall and movement is seated near river level. The composition of this colluvium varies between intermixed overburden soils and bedrock material, depending on the slope stratigraphy (Tedder, 1986).

The bedrock beds dip at 0.28 ° to the southwest. Babcock (1974) stated that the joint sets in the bedrock consist of two orthogonal systems. One strikes at 140 ° and 55 ° and the other at 05 ° and 95 °. These joint sets, which are attributed to the extensive fracturing are thought to be the result of stresses imposed by the Laramide Orogeny. The jointing patterns in the surficial glacial deposits often form parallel and perpendicular to the river valley wall and parallel to the joint pattern of the bedrock.

The soils was determined to be deep, well to moderately drained and holds moisture well (Alberta Agriculture, Provincial Base Map, 1983). It is a chernozemic soil developed on calcareous lacustrine sediments. The texture is silty loam (loam by definition is a soil composed of 20% clay , 40 % silt, and 40% sand on average) (Soil Research Institute, Soil Survey of the Edmonton Map, 1962). The surface salinity of the soil (at depth of less than 60 cm) affects less than 1% of the area and it can be found just in depressions, potholes and sloughs. Also, the subsurface salinity affects less than 5% of the area (Agriculture Canada, Soil Salinity Map, 1988). The study area is part of a larger area classified as the one with 5 to 25 % of its surface covered with wetlands (EMR Canada, Wetland Map 1981).

### 3.3 - BURIED CHANNELS

As was mentioned in the geological history section (Sec. 2.3.1), in response to the continued uplift of the Rocky Mountain during the Tertiary Period (from 65 to 2 My B.P.), erosion caused significant deposition which produced gravel plains. Meanwhile, the rivers cut down through them. In time, the uplift slowed and the rivers deprived of sediments, cut down, even at greater rate, not only through the alluvium but also into the bedrock. As a result of these millions of years of subaerial weathering and erosion, broad preglacial valleys appeared. In the Edmonton region, the erosional landscape of the bedrock is buried by the Empress Formation whose genesis has already been explained in Sec 3.2.

The other type of buried channel in this area, besides the buried preglacial valleys, is the buried meltwater channel. Godfrey (1993) noted that the crucial issues of the buried meltwater channels are the instability and high porewater pressures in soft tills, which in fact are just glaciofluvial sands in those channels.

Yoon and Vander Pluym (1974) stated that the bedrock was soft and did not pose much resistance to erosion. Its upper surface has been highly dissected by the preglacial fluvial activity. These buried bedrock channels, filled and covered with till, glaciolacustrine sediments and postglacial alluvium, are very important for the stability study of the North Saskatchewan River. Their valley floor and valley walls contribute to define the bedrock surface. These channels were drainageways for the ice sheet during the glacial period, and naturally, they received large quantities of glacial sand and gravel as outwash. They are usually filled with sands and gravel at their base, therefore, they act as a discharge path for the groundwater of that area and increase the local stability of the river bank.

It is clear from the bedrock topographic map (Kathol and McPherson, 1975) that the buried preglacial channel valley walls have specified the thalweg of the North Saskachewan River and the amplitude of the meanders (Fig. 3.1).

As mentioned by Yoon and Van der Pluym (1974), the most obvious bedrock valleys in the Edmonton area are occupied by the North Saskatchewan River and its major tributaries. However, if the bedrock could be viewed without its surficial cover then a second major system of bedrock valleys would be apparent (Fig. 3.1). The largest buried valley in the Edmonton area is called the Beverly Valley which has been traced throughout Alberta.

In the vicinity of the Lesueur and Oldman landslide successions, the Beverly valley extends towards the northeast. The North Saskatchewan River valley extending east and north, is coincident and in full hydraulic connection with it. In other words, the North Saskatchewan River has found its old channel. A tributary valley to the Beverly Valley was previously mapped to the southwest of the Lesueur landslide succession extending in a northwest direction; and it was named Boag valley (Yoon and Van der Pluym, 1974), (Fig 3.1).

The Beverly Valley is up to 8 km wide and 60 m deep with a gentle sloping valley walls up to 1.1°. The valley floor gradient is about 0.02°. The Stony Valley is a main tributary of the Beverly Valley to the northeast. It joins the Beverly Valley to the southwest of Edmonton. It is narrower and steeper, about 3 km wide and 30 m deep with side slopes up to 2° . The Stony Valley floor gradient is 0.05 °. The Namao Valley is a

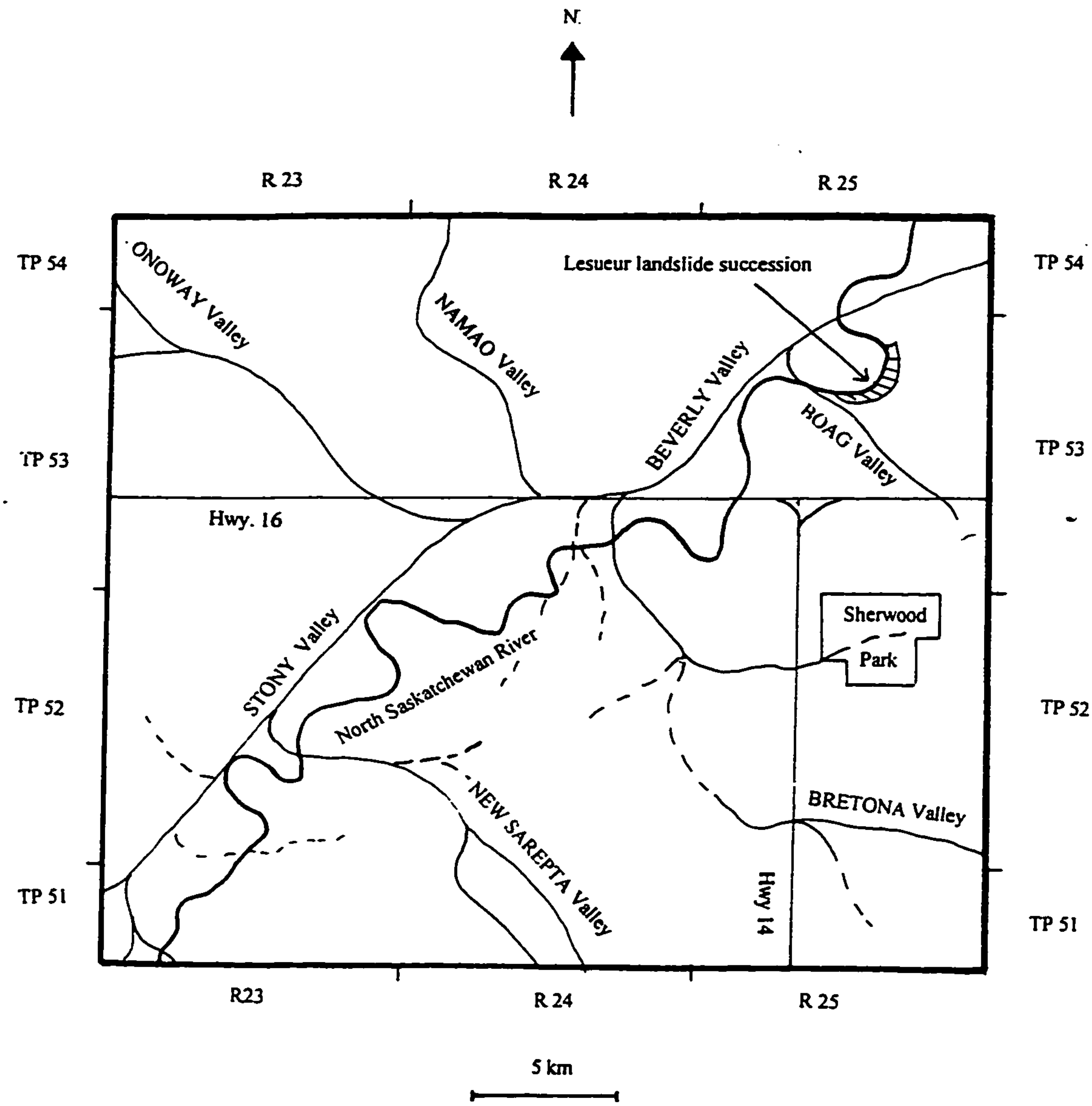



Fig. 3.1- Thalwegs of the preglacial valleys (adapted and modified from Kathol and McPherson, 1975)

minor tributary of the Beverly Valley originating 16 km north of the North Saskatchewan River and extending southeast to join the Beverly Valley. It is 3 km wide with a depth of 8 to 30 m and side slopes of up to 1.1°, with a relatively high gradient of the valley floor at 4.5 ° (Kathol and McPherson, 1975).

It is evident from the bedrock topographic map as part of Edmonton Urban Geology (Kathol and McPherson, 1975) that there are some locations southwest of the Clover Bar Mine where the North Saskatchewan River has chosen the thalweg of the preglacial valley. At those locations, the preglacial valley is narrower and steeper, therefore, the amplitude of the North Saskatchewan River meanders are smaller compared to the northeast of the Clover Bar Mine which covers the landslide successions. The preglacial valley at the location of the landslide successions is much wider, also the meander amplitude of the North Saskatchewan River is larger.

There are many tributaries of the North Saskatchewan River that in their postglacial activities have deeply incised into the bedrock. These postglacial activities have left some narrow and steep valleys such as Mill, Whitemud, Blackmud and specially Oldman Creek which is located at the study area (Kathol and McPherson, 1975). Also, this situation is observed on the bedrock topography map (Kathol and McPherson, 1975). Southwest of the Clover Bar Mine, the bedrock contours follow the North Saskatchewan River thalweg, but this is not the case northeast of the Clover Bar Mine, which is the landslide successions area.

## 3.4 - HYDROGEOLOGY

A comprehensive hydrogeological investigation has been carried out (City of Edmonton, 1990). The following is a summary of that investigation. The regional groundwater flow system is strongly influenced by the proximity of the North Saskatchewan River. Groundwater flow is towards the river valley within surficial deposits or bedrock at elevations above the base of the valley. Above the valley base, there is a strong component of downward groundwater movement relative to the water table. Discharge areas are common along the base and sides of the river

Two small preglacial channels were found south of the Lesueur landslide succession during the investigation for Edmonton Waste Management Center project (City of Edmonton, 1990). They contain sand and gravel and different flow systems have been formed within them. The hydrogeological units of the area are as follows.

Channel sands Unit

These sands, normally 11 m in thickness, are poorly sorted and range from fine sand to coarse gravel. In general, the coarsest deposits have been found at depth, as a result of fluvial processes. Petrographic analyses showed that the sand grains are mostly composed of quartzite and Canadian Shield rock fragments are absent.

Terrace sands Unit

This unit is located on the bedrock high between the eastern and western preglacial channels and is up to 10 m in thickness. However, it thins towards the escarpment to less than a meter thick. The mineralogy of the terrace sand samples was identical to that of the channel sands.

Thrust Shale - Lower Till Unit

It is more than 10 m in thickness, primarily bedrock of the Horseshoe Canyon Formation, and has a basal unit named Lower Till. This till has a very high clay content and high plasticity.

Till Unit

This unit is continuous across the area and contains a few thin, discontinuous, sand lenses.

Lacustrine Unit

This unit has 40 to 60 % clay mineral content and is the surface material.

Hydraulic Conductivity

The hydraulic conductivity parameters were measured by two methods, usually rising head method and for the channel sand unit, the method of drawdown measurements during pump tests was used (Table 3.1).

Table 3.1 – Hydraulic conductivity of the hydrogeological units of the area

| *HYDROGEOLOGICAL UNIT* | *HYDRAULIC CONDUCTIVITY (cm/s)* | *HYDRAULIC CONDUCTIVITY (cm/s)* |
|---|---|---|
| | Min. and Max. | Average |
| **Lacustrine** | $5x10^{-5}$ to $1x10^{-4}$ | $7x\ 10^{-5}$ |
| **Till** | $4x10^{-7}$ to $1x10^{-5}$ | $3x10^{-6}$ |
| **Thrust bedrock** | $3x10^{-8}$ to $1x10^{-5}$ | $5x10^{-6}$ |
| **Terrace sand rising head** | $7x10^{-4}$ to $2x10^{-3}$ | $2x10^{-4}$ |
| **Channel sand pump test** | $1x10^{-3}$ to $6x10^{-4}$ | $1x10^{-3}$ |
| **Channel sand rising head** | $1x10^{-2}$ to $1x10^{-3}$ | $7x10^{-3}$ |
| **Bedrock** | $7x10^{-7}$ to $5x10^{-5}$ | $2x10^{-5}$ |

The coal seam within the bedrock is estimated to have higher values of hydraulic conductivity, in the order of $1x10^{-3}$ cm/s. Overall, the Horseshoe Canyon Formation, on a regional scale, has a relatively low permeablity matrix with hydraulic conductivity of $1x10^{-7}$ cm/s which is a controlling factor in groundwater flow over any considerable distance. The thrust bedrock, as a result of experiencing stresses during transport is fractured and has higher values for hydraulic conductivity, which has the average value of $5x10^{-6}$ cm/s. Till and lacustrine units have moderately low hydraulic conductivity and sandier or fractured zones are responsible for higher values.

A pump test was carried out for the Empress Formation aquifer, and the hydraulic conductivity was calculated as $7x10^{-2}$ cm/s (with transmissivity of 185 $m^2$/day) (City of Edmonton, 1990).

<u>Groundwater Flow Systems</u>

There are four major flow systems identified for the area which are listed below:

1) a west-northwesterly flow in the southern channel sand;

2) a northerly flow in the eastern channel sand;

3) a northwesterly flow in the terrace sand; and,

4) a northwesterly flow in the bedrock.

Groundwater flow paths for the major systems excluding the bedrock within the study area are illustrated in Fig. 3.2.

Groundwater velocity and discharge for the major flow paths have been calculated from a modified form of the Darcy equation, Table 3.2, where:

$V = KI/n$

$Q = KIA$

( V: velocity, K: hydraulic conductivity, I: hydraulic gradient ,
n: porosity Q: discharge, A: cross-sectional area)

Table 3.2 – Characteristics of different flow systems at the study area

| *Flow System* | *K (cm/s)* | *I* | *A($m^2$)* | *n (%)* | *V (m/year)* | *Q ($m^3$/day)* |
|---|---|---|---|---|---|---|
| **Southern Channel** | 1x10-2 | 0.014 | 2450 | 40 | 110 | 300 |
| **Eastern Channel** | 1x10-2 | 0.023 | 3000 | 40 | 180 | 130 |
| **Terraces Sand** | 1x10-3 | 0.005 | 2000 | 40 | 4 | 10 |
| **Bedrock** | 1.5x10-5 | 0.007 | ---- | 35 | 0.1 | ---- |

Southern channel flow system flows towards the escarpment and empties into the North Saskachewan River terrace below the bank. Part of this flow is expressed at the surface as a spring that flows year round and the remainder is added to the flow system in the terrace sand.

The bedrock high also confines the eastern channel, which extends up to 800 m south of the junction of Oldman Creek and North Saskatchewan River. When the channel becomes unconfined near the escarpment, there is a very steep gradient.

The terrace sand flow system receives its recharge from precipitation and unconfined portions of both channels. The groundwater flow is north-northwest, towards the escarpment. City of Edmonton (1990) stated that numerous springs were observed along the slopes of the North Saskachewan River and in Oldman Creek and thomson creek.

Bedrock flow system has a low horizontal flow velocity as an average even when choosing a conservative K value. Horizontal flow is considered to be the major component of groundwater movement due to the horizontally bedded structure and thick shale aquitards. A direct comparison of the potentiometric levels showed that the gradient between the drift and the upper bedrock is 0.2 while between the upper and the lower part is 1.0. It is quite likely that there are two bedrock flow systems, one shallow and one deep. The deeper system is controlled by regional parameters, and the proximity to the river valley, while the shallow system is influenced by the saturated drift. There is not a good connection between these two systems, terrace sand and the upper bedrock flow systems. This is evidenced by the lack of groundwater mounding in the bedrock under the channels and the absence of significant dewatering of the terrace sand produced by vertical seepage through the bedrock.

Groundwater fluctuations

The seasonal fluctuations found in groundwater are directly related to precipitation (Table 3.3). Frozen ground during winter months is limited to the recharge area so that the ground water level decline until spring and summer when infiltration again becomes significant. The water levels in the sand unit, Empress Formation, and in shallow bedrock show very small fluctuations.

Table 3.3 – Groundwater level fluctuations in different hydrogeological units

| *Hydrogeological unit* | *High Water Level* | *Low Water Level* | *Fluctuation ( m )* |
|---|---|---|---|
| Till | July | March/April | 0.5 |
| Sand | May | April | 0.2 |
| Thrust Bedrock | Oct. | April | 0.4 |
| Bedrock, Shallow | May /June | March | 0.2 |
| Bedrock, Deep | June | April | 0.3 |

During the subsurface investigation of the Lesueur landslide by Painter (1965) 13 boreholes were drilled and piezometers were installed to measure the groundwater level fluctuation (Fig. 3.2). Tips of the piezometers 4 and 5 were located at the coal seam of the bedrock; their boreholes were situated beyond the right lateral margin of the landslide. The tips of the piezometers 7 and 8 were at the clayshale layers of the bedrock; their boreholes were on the displaced material of the landslide. See Fig. 3.3 for the locations of piezometers.

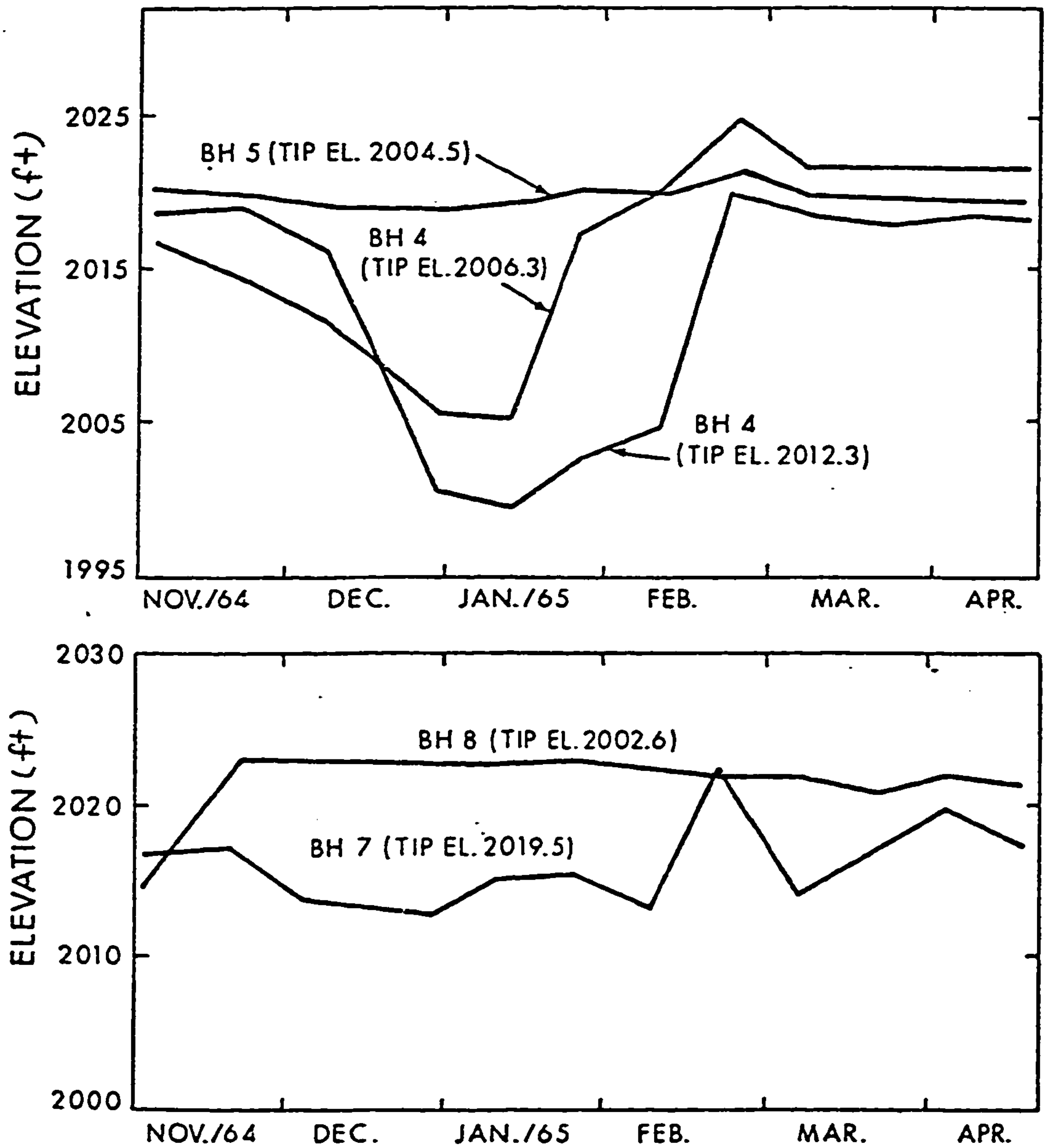



Fig. 3.2 - Piezometric data showing groundwater level fluctuations at the Lesueur landslide (after Thomson, 1971)

## 3.5 - RIVER CHANNEL TOPOLOGY

A hydrographic investigation was performed by J. A. Davis in 1996 to define the river channel configuration. The measurements were taken along 6 lines, whose locations are shown in Fig. 3.3. The transverse profiles of the river +channel, D-1 to D-6, are presented in Figs. 3.4 to 3.9.

Considering Table 3.5, summarized from these river channel transverse profiles, the following properties are calculated. The south river channel wall is steeper than the north side, having average slopes of 8 ° and 3 ° , respectively. Stations 3 and 4 show considerably higher slopes compared to the other part of the south channel wall, 26 ° and 11.6 °, respectively; while the other stations at this channel wall have slopes of 6° to 7°. Table 3.5 shows that the south wall of the river channel, along the central part of the Lesueur landslide toe (Loc. 9), which is limited by lines D-3 and D-4 is steeper than other parts of the river channel wall.

The North Saskatchewan River shows two thalwegs, the distinctive one extends through almost middle of the channel and the defuse one which is closer to the bank, along the Lesueur landslide toe.

Table 3.4 - Slope Geometrical Properties of the River Channel walls at the Lesueur Landslide Location

| *Station No.* | *South River Channel Wall (°)* | *North River Channel Wall (°)* |
|---|---|---|
| 1 | 10 | 4.5 |
| 2 | 5.7 | 2.3 |
| 3 | 26.0 | 4.9 |
| 4 | 11.6 | 2.8 |
| 5 | 6 | 2.6 |
| 6 | 7 | 3.0 |
| Average | 8( not considering stn. 3) | 3.4 |

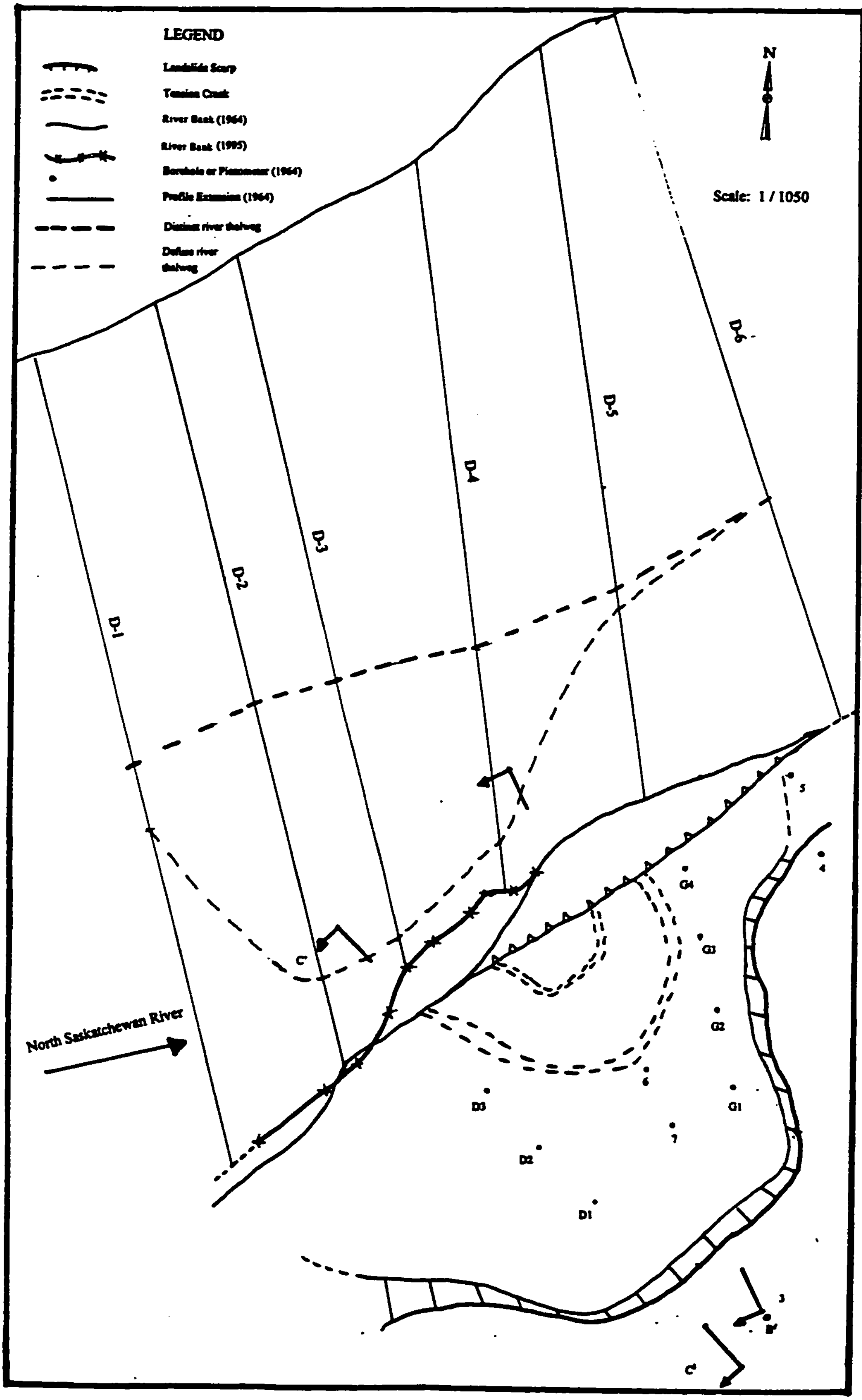



Fig. 3.3 - Location map of the profiles carried out for the river channel topology investigation

*Fig. 3.4 - River Channel Profile, D-1, (looking downstream)*

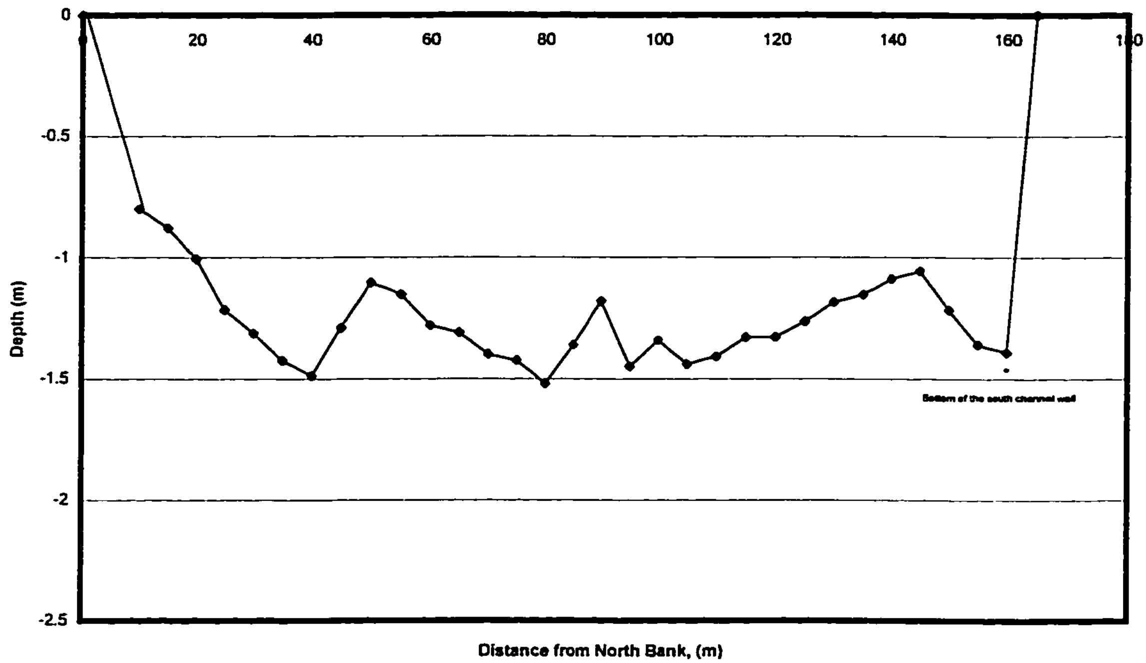



*Fig. 3.5 - River Channel Profile, D-2, (looking downstream)*

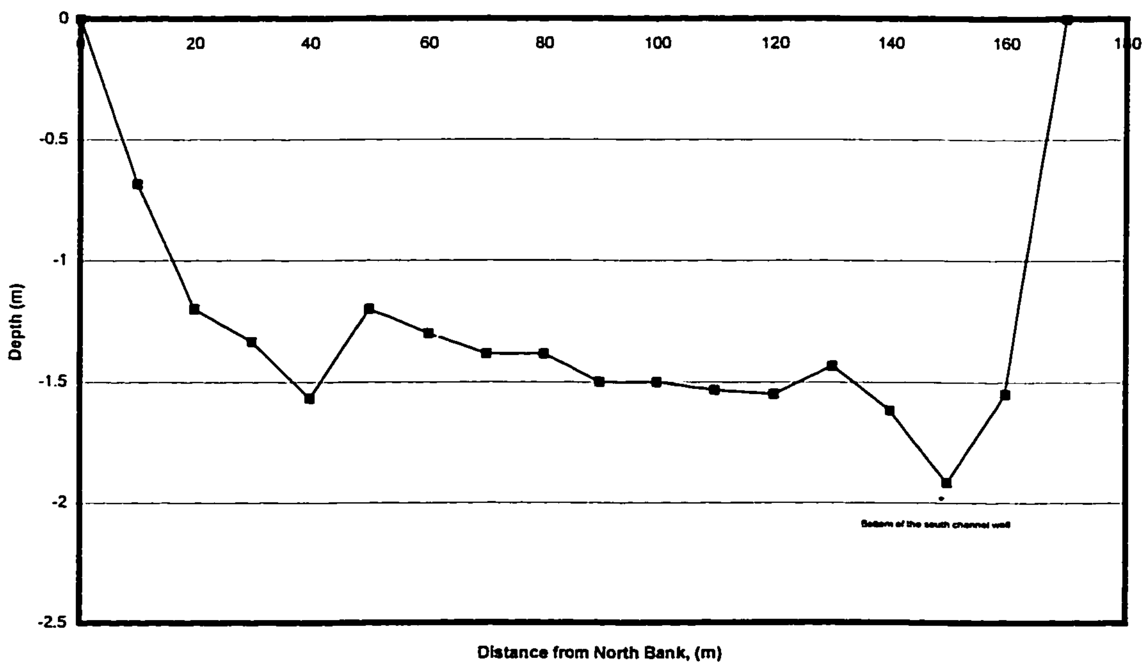


*Fig. 3.6 - River Channel Profile, D-3 , (looking downstream)*

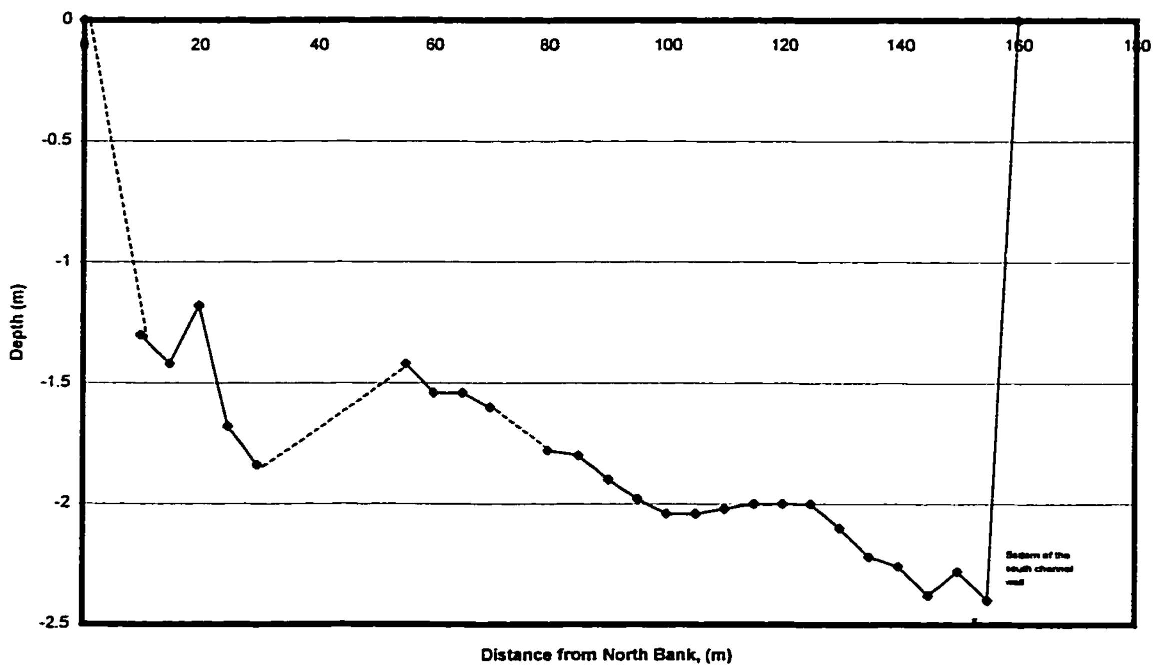



*Fig. 3.7 - River Channel Profile, D-4, (looking downstream)*

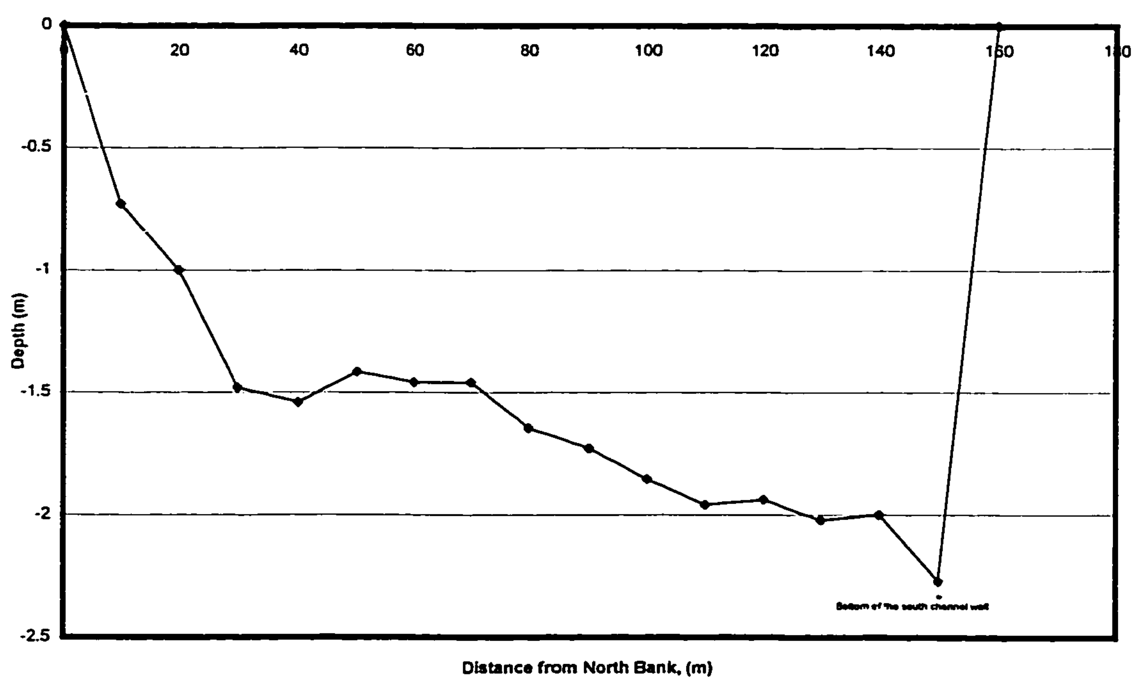


*Fig. 3.8 - River Channel Profile, D-5, (looking downstream)*

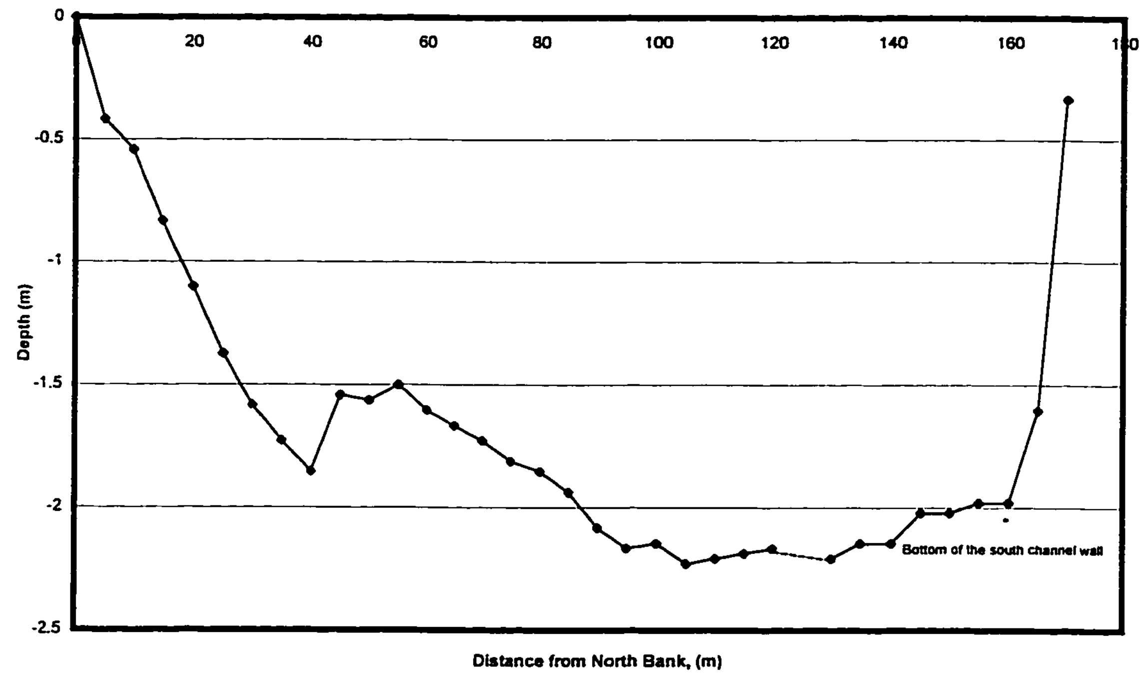
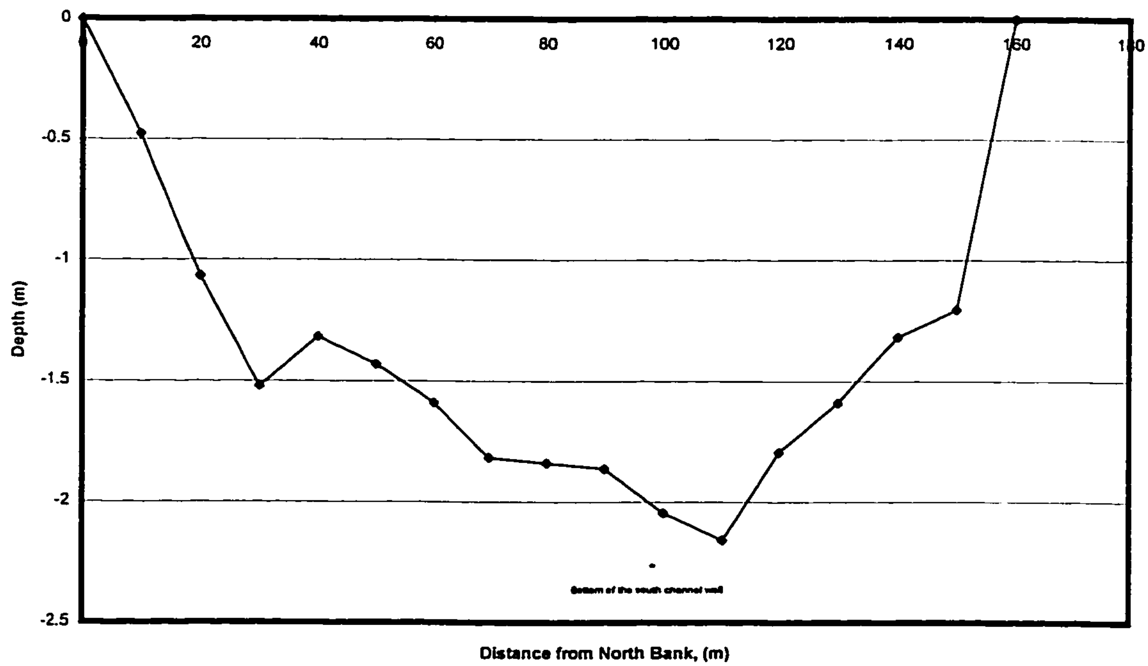



*Fig. 3.9 - River Channel Profile, D-6, (looking downstream)*



### 3.6 - CONCLUSION

The following are the conclusions of my analyses. The south wall of the North Saskatchewan River channel is steeper than its north wall. The south wall itself is steeper along the segment between profiles D-3 and D-4.

The channel at the south bank is deeper and the thalweg of the river is situated closer to the south bank. This could have resulted from the scouring by river along south bank (Fig. 3.3).

As the bedrock topographic map indicates, the bedrock surface contours are not parallel to the North Saskatchewan River thalweg in the study area. Therefore, it is concluded that the bedrock surface has been defined preglacially for the most part.

The following is a concluded from groundwater observations. The fluctuation of the water table has decreased the shear strength of the bedrock at Loc.9. This fluctuation in turn can also have resulted from the pore pressure building up by the freezing soil (and not just the increasing river discharge) (Thomson, 1971).

# Chapter 4 MASS STRUCTURAL PROPERTIES

## 4.1- OBJECTIVES & PROCEDURE

The structural properties of the mass comprising the valley wall were determined by the stratigraphic investigations. This investigation leads to identifying the geological structure and lithology of the mass along the landslide successions. The investigation includes three traverses (Fig. 4.1). The traverse S-S' extends along the outside bend of the North Saskatchewan River meander, starting from upstream of the Lesueur landslide to downstream of the Oldman succession, in order to cover the entire length of both landslide successions. Locations 0 to 38 are covered (Fig. 4.1).

The second traverse, T-T ', starts at the confluence of the Thomson creek and progresses to its source covering locations 50 to 65 (Fig.4.1). The third, O-O', begins at the confluence of Oldman Creek and goes upstream for a length of almost 1 km, which covers location 70 to 76 (Fig.4.1). See Figs. 2.4 and 2.5 for the map of the locations 0 to 38 and 50 to 65. Along these traverses, at 72 locations, colluvium was removed as much as possible to see the undisturbed layers, examine the lithology, measure the thicknesses, the elevations of the layers and collect the structural geology data. However, not all of the 72 locations have been shown on the map unless they indicated new information.

The stratigraphic columns, along these traverses, are shown on Figs.4.2 and 4.5, respectively for the traverse S - S' and T -T '. The view is as if standing at river level and looking to the upland area while the upstream is the right hand side of the viewer. These

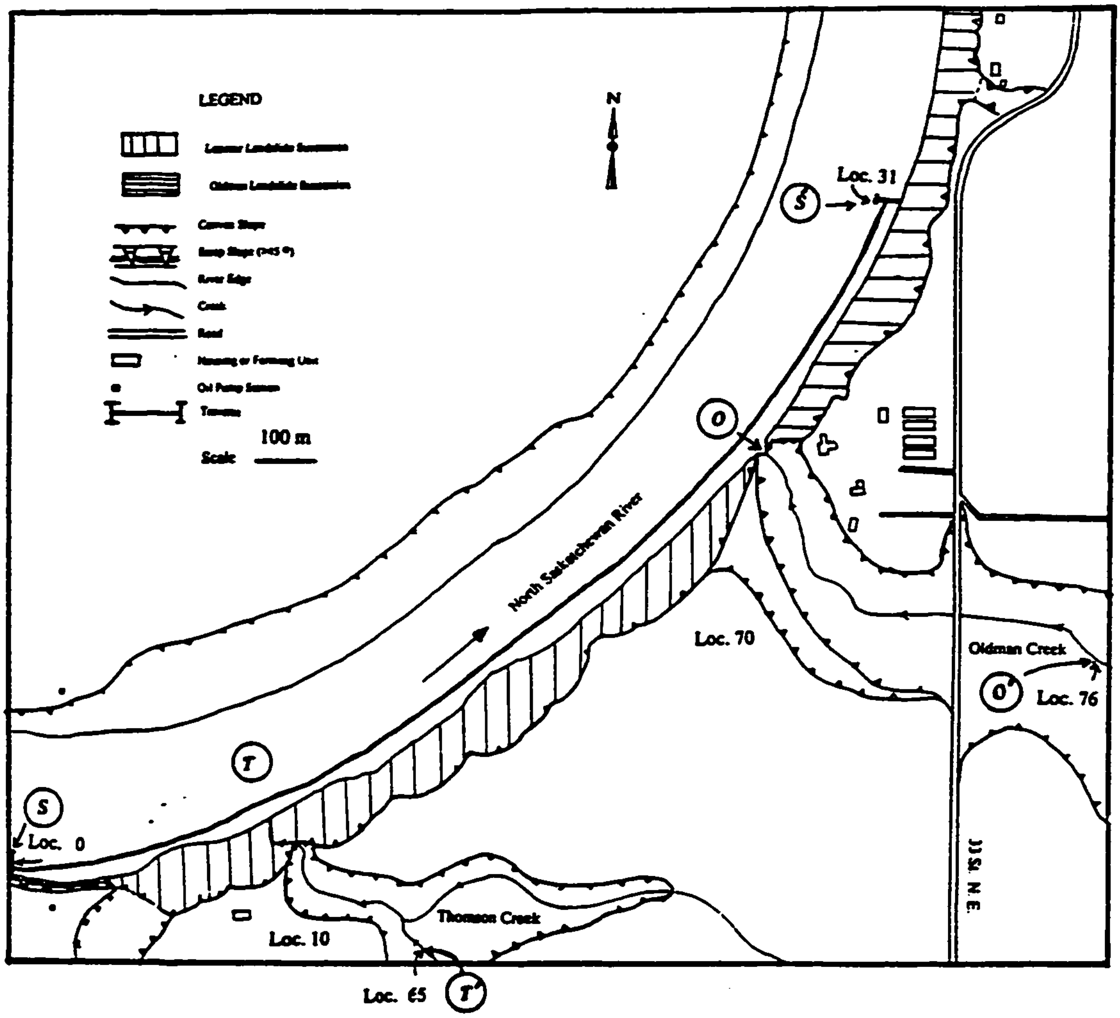



Fig. 4.1 - location map showing traverses carried out for the stratigraphic investigation. Traverse S-S ' is in NE-SW direction and it actually extends up to downstream of location 38. As the locations downstream of Loc. 31 add no extra information to the stratigraphic investigation, they have not been shown. Traverse T-T ' and Traverse O-O ' are in SE-NW.

views have been chosen for a better visualization when constructing a block diagram for the area. Any specific or extra observations are explained in sections describing the stratigraphy along those traverses. Among all the locations examined, just those that are representative of the area and show useful information are illustrated and those that add no extra information have been omitted.

## 4.2 – OBSERVATIONS & RESULTS

**- Stratigraphic Columns at traverse S-S'**

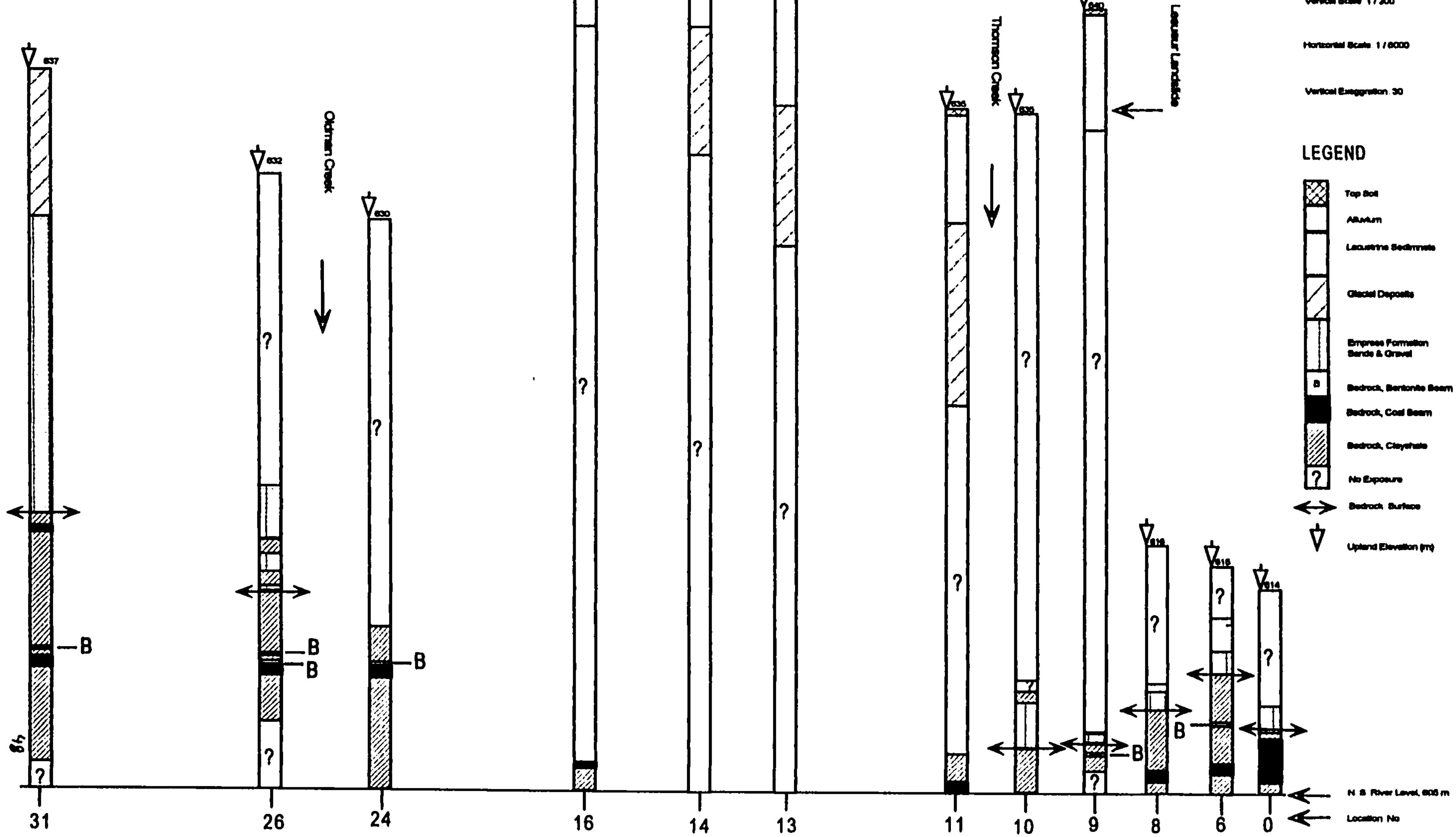
Figure 4.2 shows the stratigraphic columns along this traverse, which extends in a northeast-southwest direction.

At location 6, observation of an unusual situation in structural geology is important which is as follows. The clay shale layers of the bedrock are dipping at 25-30 ° towards the northeast instead of southwest.

The noticeable structural feature observed between Loc. 0 and Loc. 8 is the existences of two sand filled channels. They are 8 to 10 m wide and their floor is at the North Saskatchewan River level.

Overall observation for traverse S-S', is that the bedrock surface drops from Loc. 6 to Loc. 9. From the Loc. 9 moving downstream up to Loc. 10 the bedrock surface remains at the same elevation. The elevation of the bedrock surface could not be measured between Loc. 10 to Loc. 24. As the stratigraphic columns show, Fig. 4.2,

**Fig. 4.2 - Stratigraphic Columns along the S - S ' Traverse, North Saskatchewan River**



the bedrock surface again rises from Loc. 26 to Loc. 31.

This situation, rising bedrock surface on both sides of the Lesueur landslide, Loc 9, is illustrated in Fig. 4.3 +with a vertical exaggeration of 20. In addition to displaying the structure in this figure, the overall lithology is shown. It is clear that the Empress Formation sands and gravel thicken considerably and the till thins, considerably downstream, Loc. 31. Consequently, most of the surficial deposits overlying the bedrock at the downstream slopes are comprised of the sands and gravel of the Empress Formation.

In order to facilitate the presentation of the structure by the sketches and block diagram, Fig. 4.3 has been simplified to Fig. 4.4. The area shown in Fig. 4.4 is limited between Loc.9 and Loc. 31. In Fig. 4.4, the change in upland topography is eliminated. As the actual change in the upland elevation is about 4 to 5 m. Ignoring the vertical exaggeration of 20, the change in the upland elevation would not be visible. The bedrock surface apparent dips and the situation of pinching out for the layers have been emphasized. The contact line between till and the Empress Formation sands and gravel is estimated based on just two locations 9 and 31. The North Saskatchewan River level has been obtained by means of the orthophoto map by the City of Edmonton (1991).

At downstream, Loc. 25, 26 and 31, I noticed that the bentonite seam and also the coal seam elevations are higher, 610.5 m , rather than 605.5 m upstream. This is consistent with the literature stating that the bedrock layers dip at 0.28 ° to the SW.

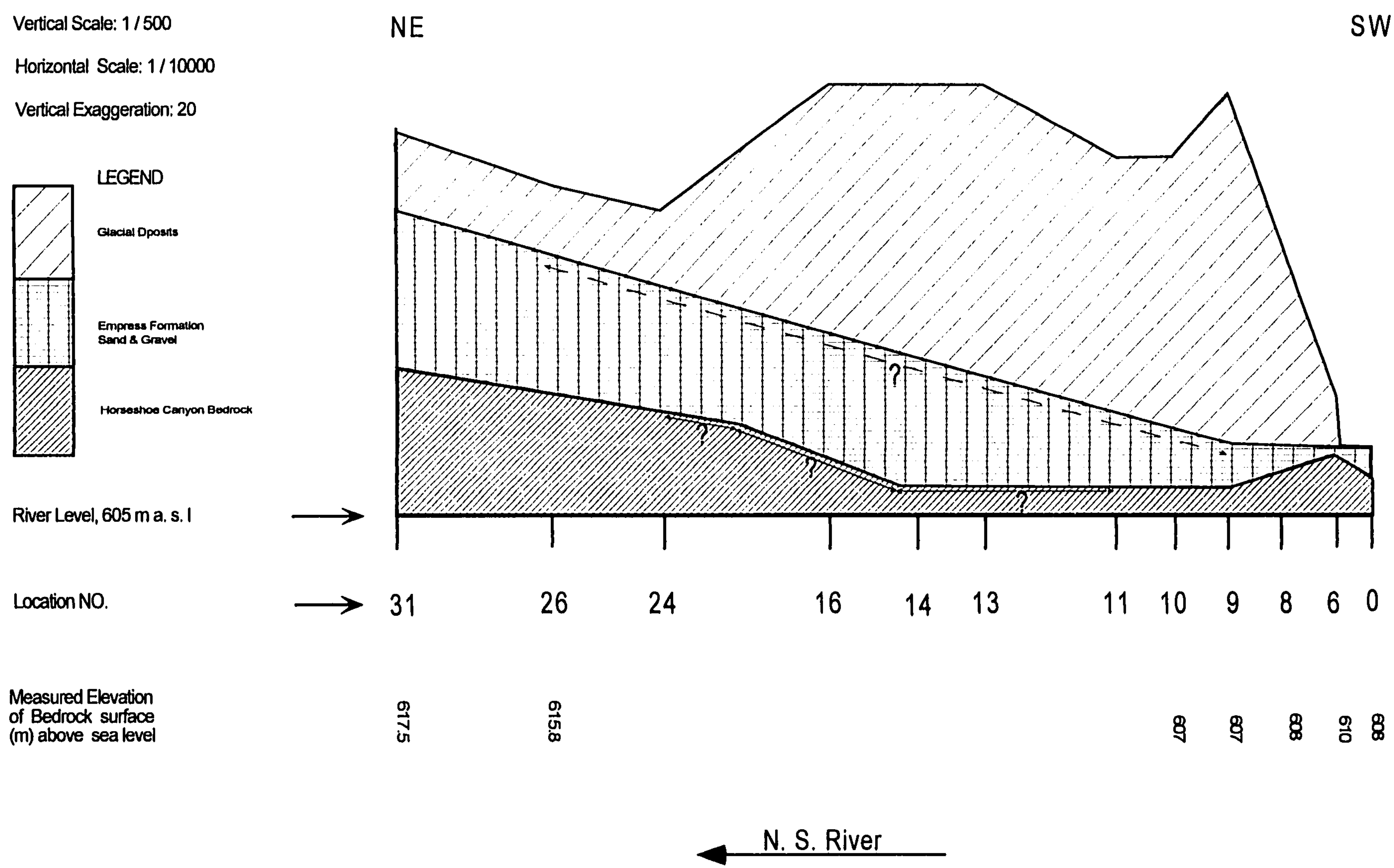



**Fig. 4.3 - Geological Cross-Section along the S-S ' Traverse, North Saskatchewan River**

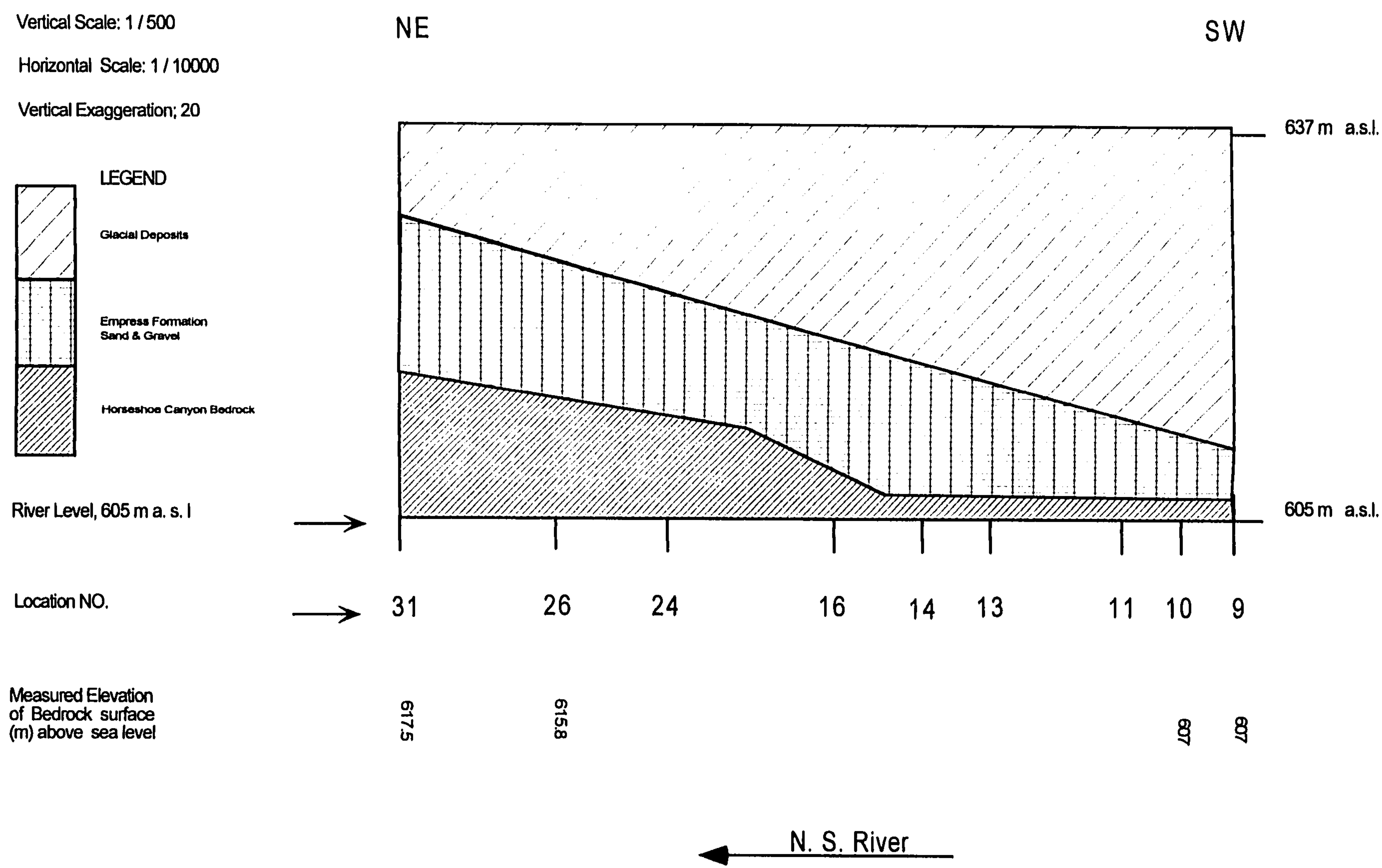



***Fig. 4.4 - Simplified Geological Cross-Section along the S-S ' Traverse, North Saskatchewan River***

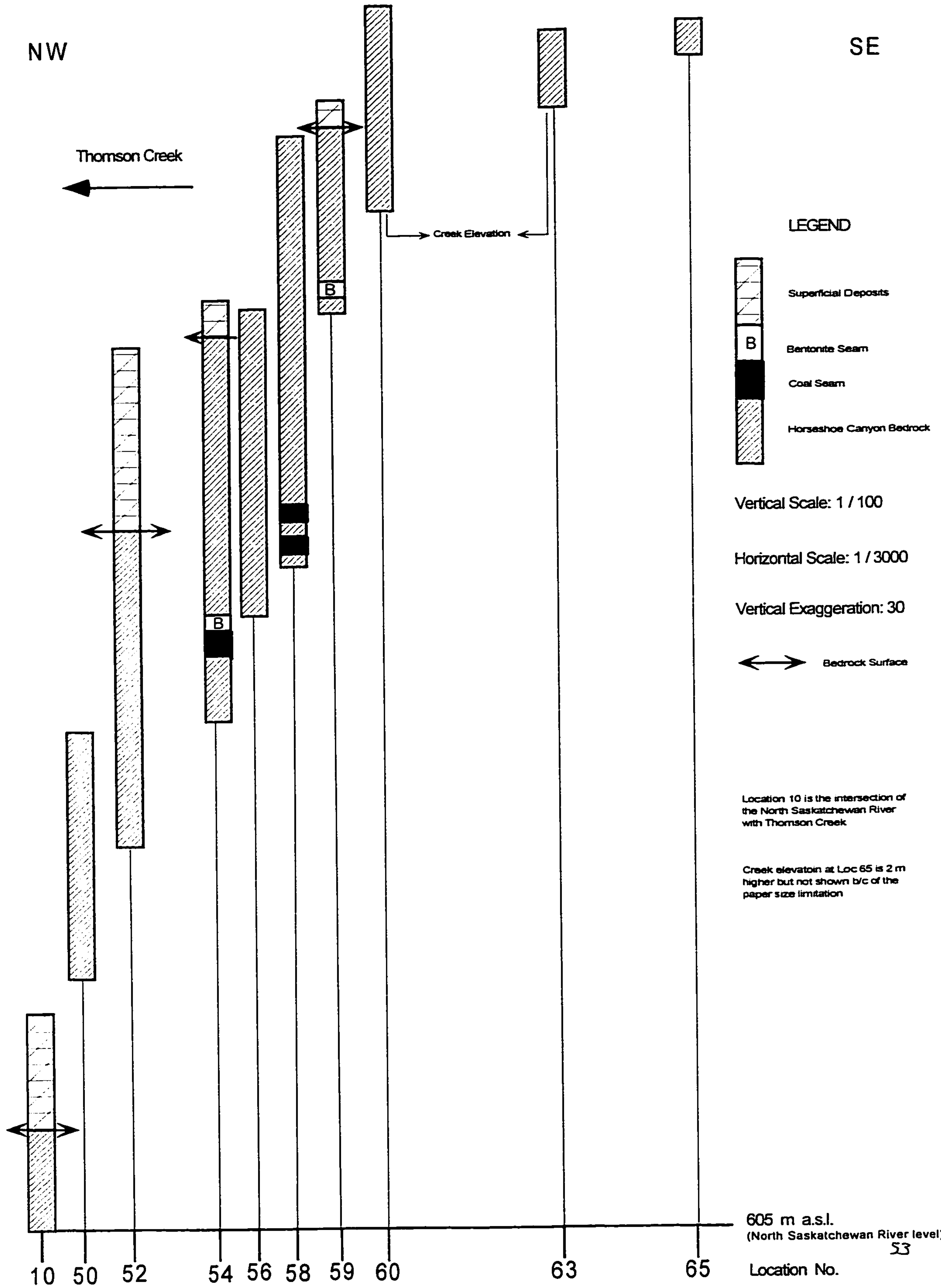
**- Stratigraphic Columns along traverse T-T '**

Fig. 4.5 shows the stratigraphic columns along this traverse, thomson creek, which extends in a southeast-northwest direction. Again, the view is as if standing on the creek level and looking to the upland while the upstream is on the right hand side. The bedrock surface defined by means of the stratigraphic investigation along this traverse includes two parts. The upstream part which dips at 3.3 ° to NW ( ~ 315 ° / 3.3 ° ) and the downstream part dipping at 16 ° to NW ( ~ 315 ° / 3.3 ° ) for about 50 m southeast of the intersection of the thomson creek with the North Saskatchewan River, Fig. 4.6.

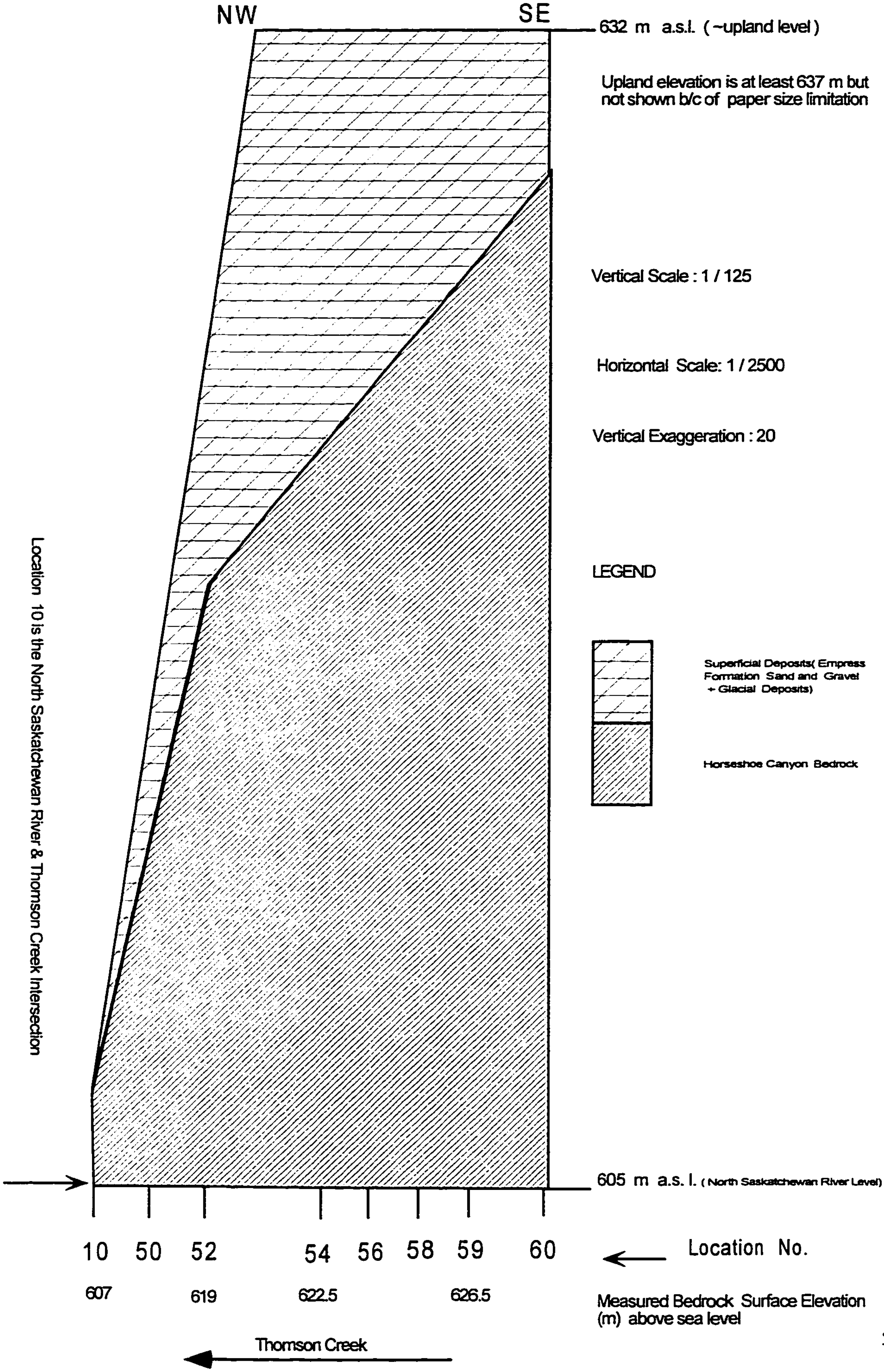
**- Stratigraphic Columns at traverse O - O '**

Seven locations along this traverse have been investigated. However, the usual exposures that I was able to make, were only 3 to 4 m high and only the bedrock layers were observed, e.g. location 53, which is 900 m SE of the Oldman Creek intersection with North Saskatchewan River. The highest observed bedrock layer among these locations, is Loc. 53, which is 628.7 m but still the contact between the bedrock and drift (the bedrock surface) was not visible.

*Fig. 4.5 - Stratigraphic Columns along the T - T' Traverse, Thomson Creek*



## Fig. 4.6 - Geological Cross-Section along the T-T ' Traverse, Thomson Creek



## 4.3 – DISCUSSION

Along traverse S-S', the elevation of the bedrock surface is unknown from Loc. 11 to Loc. 24 because of inability to make an exposure. It would be reasonable if the bedrock surface is extended from Loc. 10 towards downstream and also from Loc. 26 towards its upstream. Consequently, the configuration represented in Fig. 4.3 for the bedrock surface is suggested.

It is postulated that this bedrock surface has been produced by ice thrusting, as the following reasons support this idea. The first evidence is the bowl shape of the bedrock surface between Loc. 6 and Loc. 24. The second supporting factor for ice thrusting is the position of the minor (tributary) preglacial valley named Boag Valley at vicinity of Loc. 9, where is the upstream part of the Lesueur succession (Fig. 3.1). Third reason is inclined layers at location 6.

Limited to the bowl shape area of the bedrock, the thickness of the bedrock clay shale that overlies the bentonite seam of the bedrock is smaller than the downstream part such as Locs. 26 and 31. Therefore, it is possible that the bentonite seam limited to Loc. 6 and Loc. 24, Lesueur succession, has been softened more by ice thrusting compared to that of Oldman succession (Fig.4.3).

At traverse T-T', as Fig. 4.6 shows, the bedrock surface has a sharp break in its slope upstream of thomson creek and North Saskatchewan River intersection.

## 4.4 -CONCLUSIONS

The bowl shaped part of the bedrock surface, which is between Loc. 6 to Loc. 24, Lesueur succession, has been produced by ice thrusting. Consequently, the bentonite seam at Lesueur succession has been softened more compared to the Oldman succession.

As the bedrock surface was defined locally according to the preceding stratigraphic investigation, the following structural properties are concluded. While moving from the upstream part of the succession downstream the elevation of the bentonite and coal seams increases. This situation was expected as the literature states that the bedrock layers dip at 0.28 ° to southwest. It was found that the thickness of the Empress Formation (sands and gravel) increases downstream.

# Chapter 5 SLOPE MOVEMENT MONITORING

Three different studies have been undertaken to monitor the slope movements. One is the control surveying by A. Peterson, D. Cruden and S. Thomson which began in 1995 (Sec. 5.1). Another is the mensuration by T. J. Thomson in 1995 (Sec. 5.2). The aerial photo interpretation that I carried out is another approach taken to complete the slope movement monitoring (Sec. 5.3). The control surveying study is a quantitative approach with good precision. As its precision is +0.0001 m, the associated errors are negligible. The mensuration study is also a quantitative approach but some human and equipment errors are associated with it. As they are large (precision about + 2.5 m), they should be taken into account. The aerial photo interpretation is a qualitative approach to the slope movement monitoring.

## 5.1 – Control Surveying

### 5.1.1- Objectives and Procedure

The control surveying has been carried out by placing 29 reference hubs during July 1995 at Loc. 9, Lesueur landslide. The survey undertaken in 1995 produced a map of the Lesueur landslide (J.A. Davis, 1995) while indicating the positions of hubs set up for the monitoring (Fig. 5.1). Seven of those hubs, R6, R7, 16, 15A, 15, 22 and D3, have been monitored by control surveying in Oct. 1996, May 1997 and Oct. 1997 (at an interval of six months). Two categories of data are obtained from these measurements.

One is finding the trends and plunges of the overall displacement vectors for the displaced mass at the Loc. 9, Lesueur landslide, for different hubs. The positions of the reference hubs and their displacement vectors during the monitoring period are shown on

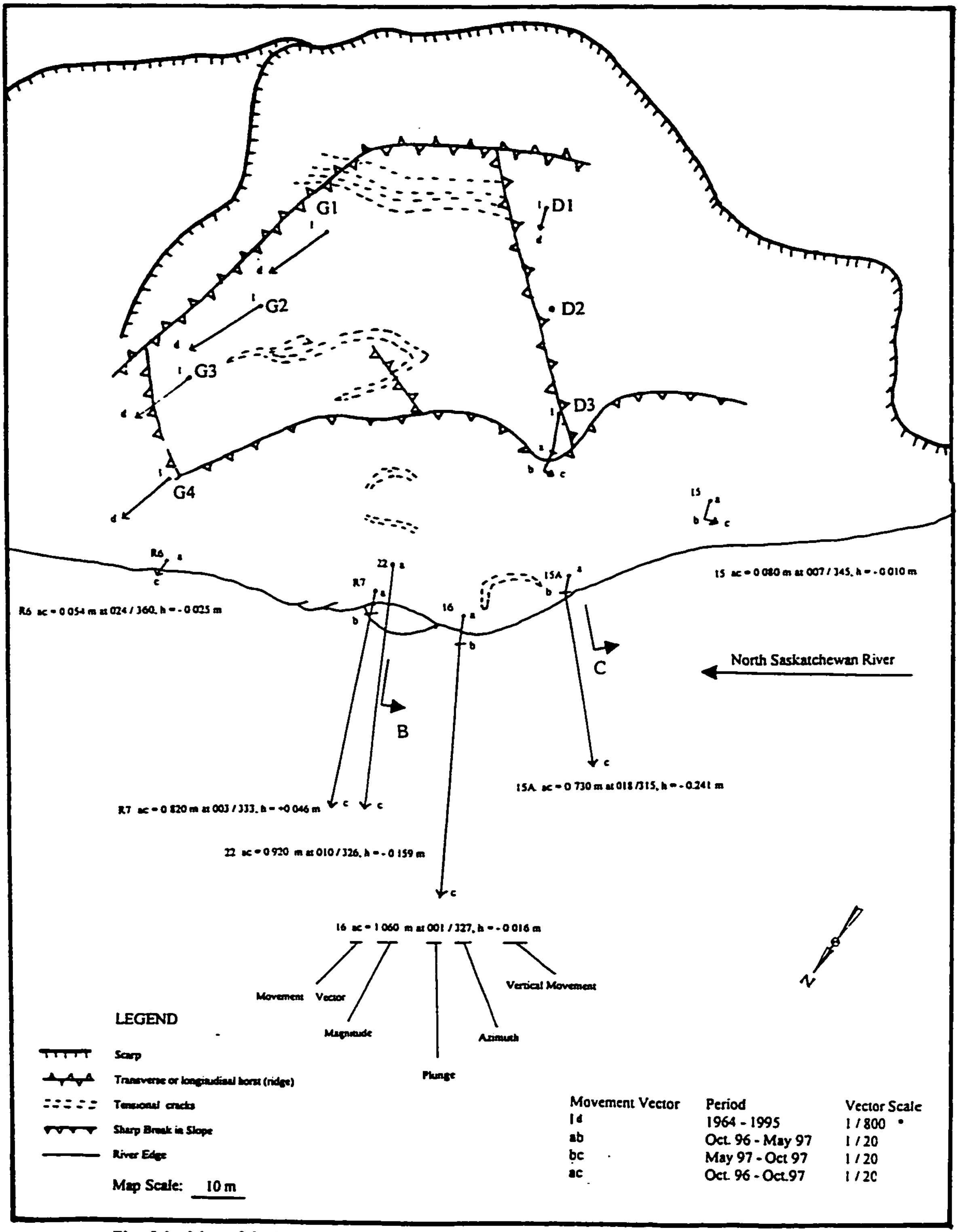



Fig. 5.1 - Map of the Lesueur landslide, Loc. 9, showing the movement vectors for the hubs during Oct. 1996 - Oct. 1997 (by control surveying). This map has been reduced from the original scale 1/ 200. Some geomorphological details omitted.

***Fig. 5.1 (b)- Longitudinal Profile(P-9A) of Lesueur Landslide, showing the displacement vectors of the D series of standpipes (1964-1995) and of typical hub movements(1996-1997)***

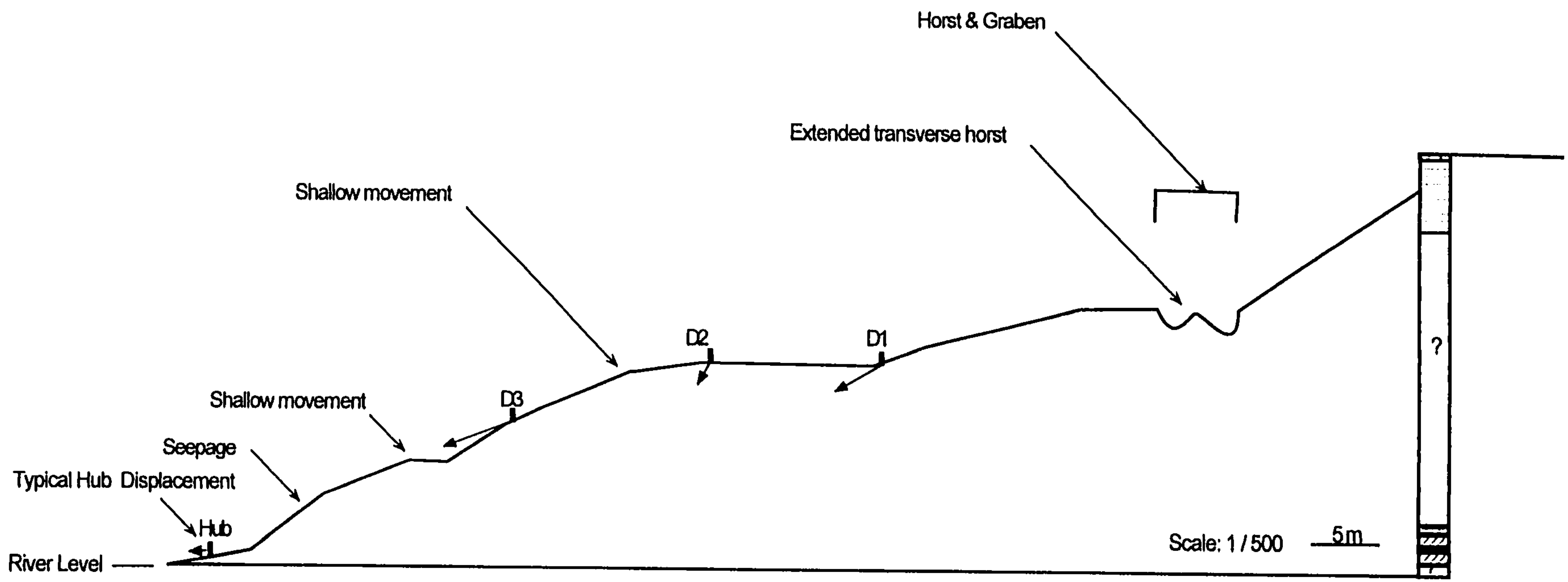


*Fig. 5.1( c ) – Longitudinal profile of the Lesueur landslide along the G series of standpipes showing their movement vectors(1964-1995)*

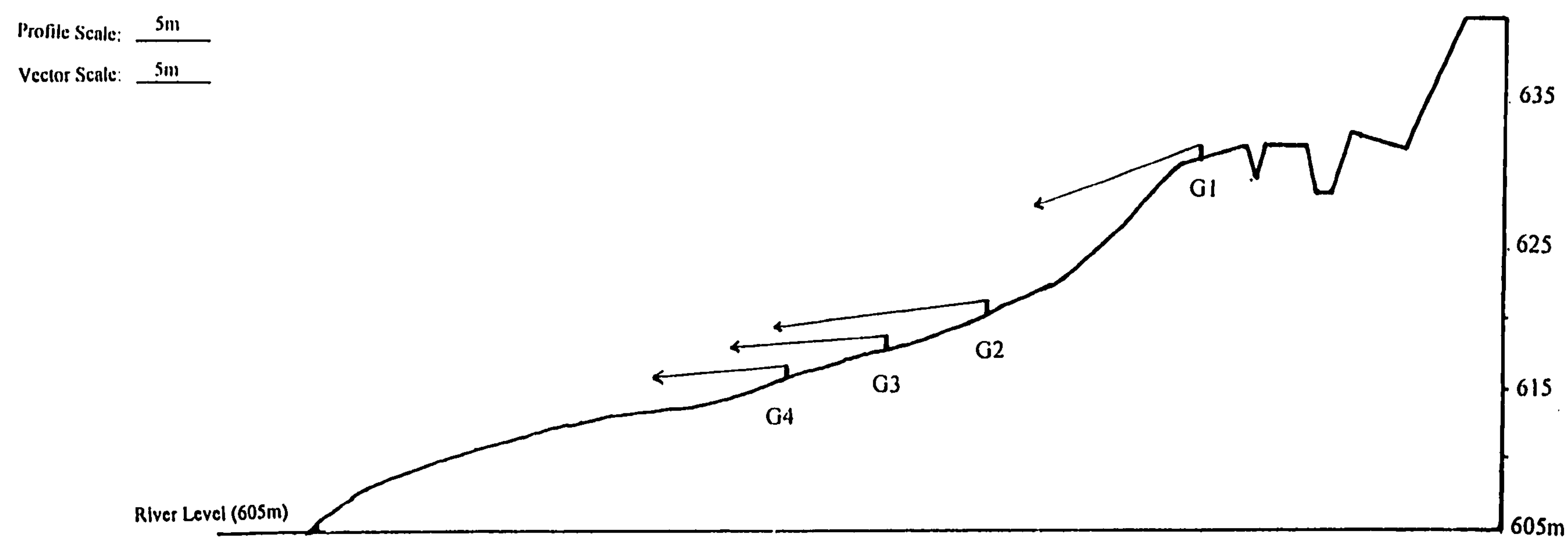


Fig. 5.1, which is reduced from the original one (J.A. Davis, 1995). In order to calculate the horizontal and vertical displacement and also the trend and plunge of the overall displacement vector for each hub, the original map (1:200) by J.A. Davis (1995) is used to minimize the error. The values from this monitoring are in Table 5.1, which represents the summarized data from the control surveying. The complete data are shown in appendix C.

The other category of the data is the magnitude and type of the total toe movement, either advance or recession of the Lesueur landslide toe, since 1964. In order to obtain this value for the period of 1964- 1995, the initial positions of the G and D series of standpipes (installed for subsurface investigations by Painter, 1964) have been located on the 1995 map, Fig. 5.2. However, this involves estimates; because all of those former hub references set up in 1964 have been lost as result of either landscaping of the upland area or the rapid growth of the underbrush, except borehole 3,.

### 5.1.2 - Erosion Survey

An erosion survey was carried out in 1996 and 1997 as it was necessary to find the following results. One is obtaining the magnitude of the river erosion, Y value, along the south bank at the Lesueur landslide toe shown in Fig. 5.3. The other purpose is to determine the overall toe movement from Oct. 1996 to Oct. 1997.

The toe movement results from two activities, the displacement of the displaced mass and the action of the river erosion.

## Table 5.1 - The Control Surveying Data and The Resultant Movement Vectors

| Hub | Period | Date | Horizontal Coordinate (m) Y | X | Movement Displacement (m) N | S | E | W | Resultant Movement Vec Azimuth (o) | Magnitude (m) | Vertical Coordinate (m) Z | Movement Displacement (m) Downward | Upward | Overall Movement (96-97) Magnitude | Plunge (o) | Trend (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15 | | Oct-96 | 9829.4288 | 10285.5745 | | | | | | | 611.8833 | | | | | |
| | Oct. 96 - May 97 | May-97 | 9829.4728 | 10285.5783 | 0.044 | | 0.004 | | 5 | 0.044 | 611.8778 | -0.005 | | | | |
| | May 97 - Oct. 97 | Oct-98 | 9829.5049 | 10285.5577 | 0.032 | | | -0.021 | 327 | 0.038 | 611.8726 | -0.005 | | | | |
| | Oct. 96 - Oct. 97 | | | | | | | | | | | -0.010 | | 0.080 | 7 | 345 |
| | | | | | | | | | | | | | | | | |
| 16 | | Oct-96 | 9866.8698 | 10307.3028 | | | | | | | 609.2551 | | | | | |
| | Oct. 96 - May 97 | May-97 | 9866.9600 | 10307.2610 | 0.090 | | | -0.042 | | 0.099 | 609.2299 | -0.025 | | | | |
| | May 97 - Oct. 97 | Oct-98 | 9867.7657 | 10306.7350 | 0.806 | | | -0.526 | 326 | 0.962 | 609.2385 | | 0.009 | | | |
| | Oct. 96 - Oct. 97 | | | | | | | | | | | -0.016 | | 1.060 | 1 | 327 |
| | | | | | | | | | | | | | | | | |
| R6 | | Oct-96 | 9886.8292 | 10347.8686 | | | | | | | 609.4405 | | | | | |
| | Oct. 96 - May 97 | May-97 | 9886.8832 | 10347.8687 | 0.054 | | 0.000 | | 0 | 0.054 | 609.4249 | -0.016 | | | | |
| | May 97 - Oct. 97 | Oct-98 | 9886.8797 | 10347.8693 | | -0.004 | 0.001 | | 170 | 0.004 | 609.4162 | -0.009 | | | | |
| | Oct. 96 - Oct. 97 | | | | | | | | | | | -0.025 | | 0.054 | 24 | 0 |
| | | | | | | | | | | | | | | | | |
| R7 | | Oct-96 | 9872.5519 | 10319.6611 | | | | | | | 609.9778 | | | | | |
| | Oct. 96 - May 97 | May-97 | 9872.6316 | 10319.6502 | 0.080 | | | -0.011 | 352 | 0.080 | 609.9656 | -0.012 | | | | |
| | May 97 - Oct. 97 | Oct-98 | 9873.3166 | 10319.3498 | 0.685 | | | -0.300 | 336 | 0.748 | 610.0238 | | 0.058 | | | |
| | Oct. 96 - Oct. 97 | | | | | | | | | | | | 0.046 | 0.821 | 3 | 333 |
| | | | | | | | | | | | | | | | | |
| 15A | | Oct-96 | 9850.2574 | 10296.8890 | | | | | | | 608.0805 | | | | | |
| | Oct. 96 - May 97 | May-97 | 9850.3203 | 10296.8553 | 0.063 | | | -0.034 | 332 | 0.071 | 608.0609 | -0.020 | | | | |
| | May 97 - Oct. 97 | Oct-98 | 9850.7615 | 10296.3574 | 0.441 | | | -0.498 | 312 | 0.665 | 607.8401 | -0.221 | | | | |
| | Oct. 96 - Oct. 97 | | | | | | | | | | | -0.241 | | 0.770 | 18 | 315 |
| | | | | | | | | | | | | | | | | |
| D3 | | Oct-96 | 9834.8402 | 10309.8828 | | | | | | | 616.4859 | | | | | |
| | Oct. 96 - May 97 | May-97 | 9834.9121 | 10309.8934 | 0.072 | | 0.011 | | 8 | 0.073 | 616.4690 | -0.017 | | | | |
| | May 97 - Oct. 97 | Oct-98 | 9834.9159 | 10309.8579 | 0.004 | | | -0.035 | 276 | 0.036 | 616.4541 | -0.015 | | | | |
| | Oct. 96 - Oct. 97 | | | | | | | | | | | -0.0320 | | 0.080 | 41 | 332 |
| 22 | | Oct-96 | 9866.4062 | 10318.7988 | | | | | | | 610.4054 | | | | | |
| | Oct. 96 - May 97 | May-97 | 9866.4760 | 10318.7836 | 0.070 | | | -0.015 | 347 | 0.071 | 610.3812 | -0.024 | | | | |
| | May 97 - Oct. 97 | Oct-98 | 9867.1741 | 10318.2904 | 0.700 | | | -0.490 | 325 | 0.854 | 610.2458 | -0.135 | | | | |
| | Oct. 96 - Oct. 97 | | | | | | | | | | | -0.1596 | | 0.920 | 10 | 332 |

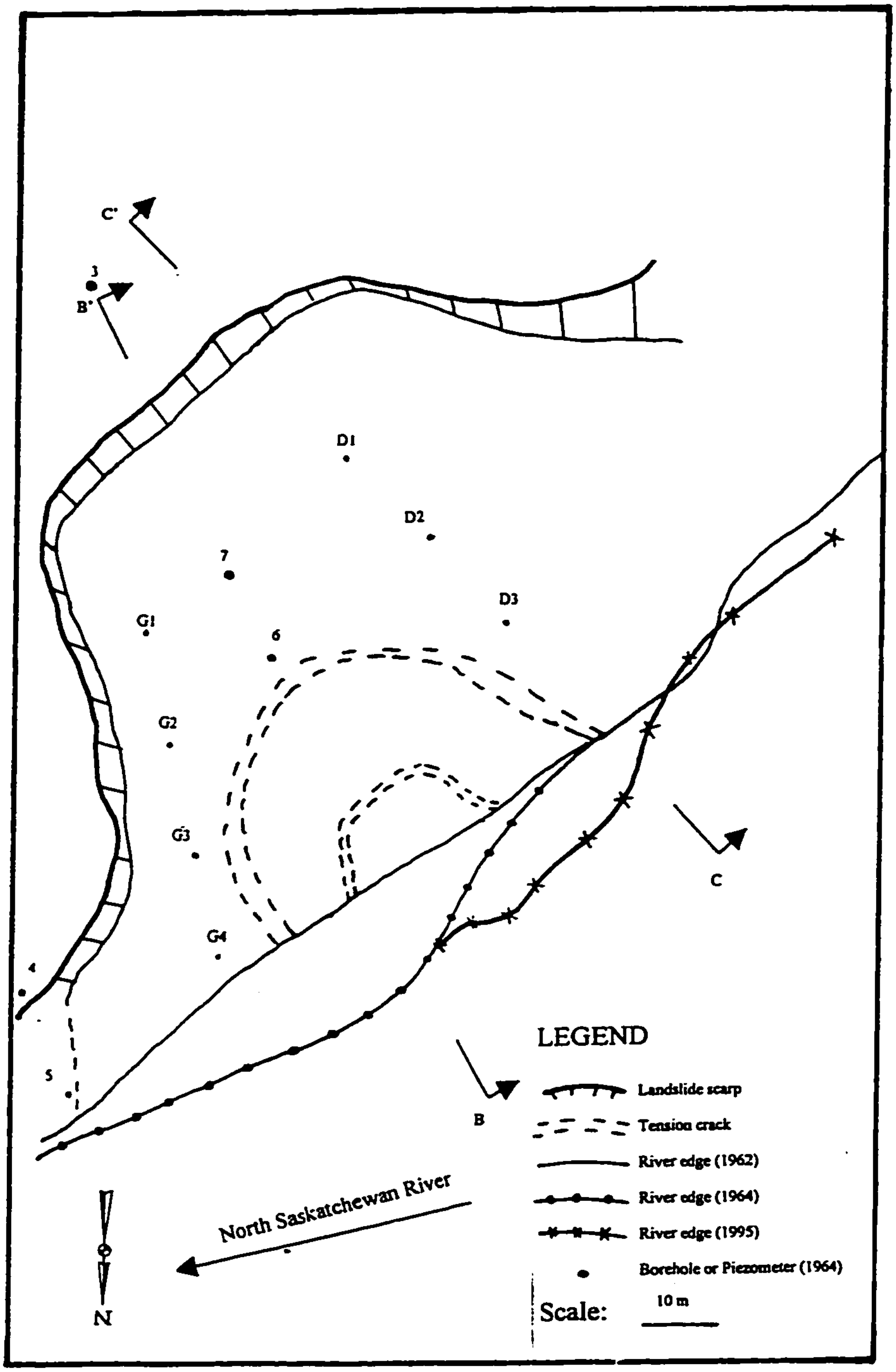
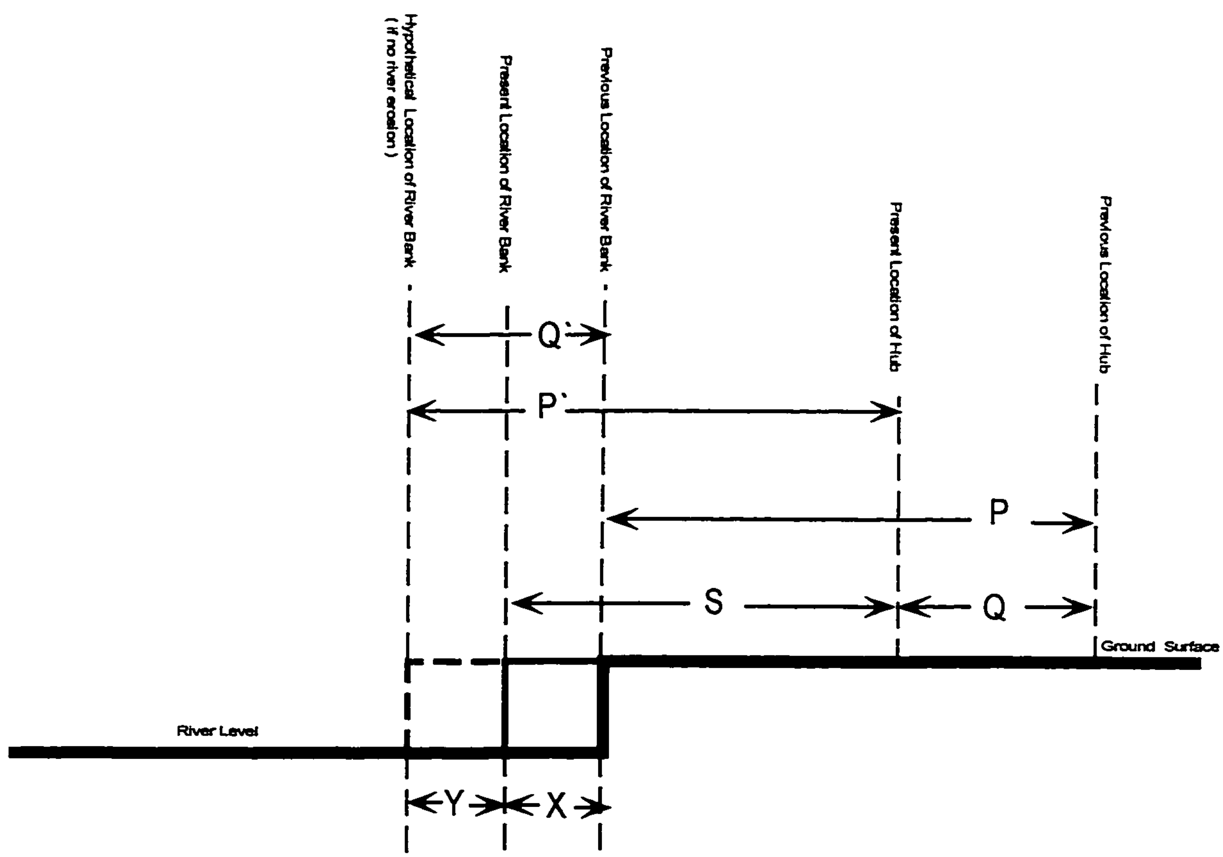



Fig. 5.2 -Projection of the south river edge from Davis' map (1995) on Painter's map (1964).The younger river edges are shown where they do not coincide with an older river edge. 1962 is the pre-sliding river edge. Profile extensions have been shown for comparison.




P: Previous distance between hub and the river bank,observed in the field by direct measurements    P = P`

Q: Displacement of the displaced mass, by control surveying

Q': The hypothetical river bank advance, Q` = Q

S: Present distance between hub and the river bank,observed in the field by direct measurements

Y: River Bank Erosion, Y = P` - S = P - S

X: Toe Movement. X= S + Q - P = Q - Y

IF: Q > Y    X > 0    Toe Advance

Q < Y    X < 0    Toe Recession

*Fig. 5.3 - Geometrical relationship among parameters measured to determine the toe movement, either toe advance or toe recession*

Fig 5.3 shows the geometrical relationship between these shifting points. Q, indicates the displacement of the displaced mass and is obtained from the control surveying for each hub between Oct. 1996 and Oct. 1997. P, is the distance between the initial position of the hub and the initial position of the river bank (toe) in a specified direction. S, is the distance between the present hub location (1997) and its present river bank (toe) in the same direction as P. The relationships required to obtain the river erosion and the overall toe movement are also represented in Fig. 5.3.

### 5.1.3 - Results

The control surveying data show the following results.

- During Oct 1996 - Oct. 1997, the hubs R7, 22, 16 and 15A have moved along vectors having trends in the range from 315 ° to 333° (Fig. 5.1). The plunges range from +3 ° to -18 ° for hubs R7, 22, 16 and 15A. Details are in Table 5.1. The hub movements indicate that at the landslide tip, the displaced materials are displacing almost horizontally.

- During Oct .1996-Oct. 1997, the magnitudes of the overall displacement vectors of the hubs are in range of 760 mm to 1060 mm if hubs 15 and R6 are excluded (Fig. 5.1).

Other results obtained from comparing the control surveying data with Painter's map are as follows (Fig 5.2).

1) 1964-1995: scarp recession was calculated to be 3.7 m

2) 1964-1995: overall toe advance along the C - C ' long profile, calculated to be +5.5m

3) 1964-1995: maximum displacement downslope for the displaced mass was found to be 10.5 m for the G series of standpipes (Fig. 5.1).

- 1964 - 1995: Based on the Table-1 in a paper by Cruden et al. (1998), the displacement vectors of the G series range from 7° to 20° and for the D series of standpipe, it varies between 20° to 55°. It worth noting that these standpipes are located in the depletion zone of the landslide while the hubs are in the accumulation zone (Fig. 5.1-b).

The results of adding the control surveying data and erosion survey data are at Table 5.2 which contains the measurements (S and P), the calculated river erosion (Y) and the total toe movements (X). The data introduced in this table are from different sources, as S values are from the erosion survey 1996-1997, P values from the map (1:200) prepared for the control surveying. It should be noted that there are some associated errors with taking the numbers from the map. Q has been taken from the results of the control surveying. It worth noting that if the river erosion for a period of time is higher than the displacement of the displaced mass, Y > Q, the result would be a negative value showing landslide toe (river bank) recession. If Q > Y, a positive number will be obtained indicating toe advance. In this case, Loc. 9, Lesueur landslide, as it is mentioned in Table 5.2, the toe has receded in range of -0.34 m to -3.18 m from Oct. 1996 to Oct. 1997. The following results are for the total toe movement at the Lesueur landslide.

Table 5.2 - Total Toe Movement (at Loc. 9) obtained from adding the control surveying and erosion survey results. Refer to Fig. 5.3 for geometrical relationship among S, P, Q, Y and X.

| | | | | | *Displacement of the Displaced Mass* | *River Erosion* | | *Toe Movement* |
|---|---|---|---|---|---|---|---|---|
| *HUB* | *P (m)* | *S (m)* | | | Oct.96-Oct.97 | *Y (m)* | | Oct.96-Oct.97 |
| | Oct. 96 | Oct.97 | June.98 | Aug.98 | | Oct.96-Oct.97 | Oct.97-June.98 | |
| R7 | 5.2 | 1.2 | 0.9 | 0.8 | 0.820 | 4.0 | 0.3 | -3.180 |
| 16 | 2.4 | 1.0 | 0.8 | 0.6 | 1.060 | 1.4 | 0.2 | -0.340 |
| 15A | 5.0 | 2.3 | 1.3 | — | 0.730 | 2.7 | 1.0 | - 1.970 |
| R6 | 1.0 | 0.9 | 0.9 | 0.9 | 0.054 | 0.1 | 0.0 | -0.046 |

### 5.1.4 – Discussions and Conclusion

The results of the control surveying, Painter's map (1965)0 and the erosion survey results are compared in Table 5.3. It should be noted that for the period of 1964-1995, X (toe movement) and Q (displacement) are known from comparison between the control surveying results and Painter's map. Subsequently, Y (river erosion) is obtained from these results. For the period 1996-1997, the opposite is the case. Y is known from the erosion survey and X was obtained, subsequently. Based on Table 5.3, the following conclusions can be made.

Table 5.3 - Movement values at the Lesueur landslide. The negative values for the total toe movement show toe recession and positive values indicate toe advance.

| *Process (units all in metres)* | *1964 -1995* | *1996 – 1997* | | | |
|---|---|---|---|---|---|
| | | **R7** | **16** | **15A** | **Average** |
| **Scarp Recession** | 3.7 | | | | |
| **River Erosion (Y)** | 18.5 (Y=Q-X) | 4.0 | 1.4 | 2.7 | 2.7 |
| **Displaced Mass Displacement ( Q)** | 24 | 0.82 | 1.06 | 0.73 | 0.87 |
| **Toe Movement, X = ( Q - Y )** | 5.5 | -3.18 | -0.34 | -1.97 | -1.83 |

The scarp has receded 3.7 m from 1964-1995. The toe has advanced +5.5 m from 1964-1995. The toe has receded -1.83 m as an average, from 1996-1997.

The question of what time this river erosion started remains to be answered by aerial photo interpretation in Chapter 5. The toe could have advanced greater than +5.5 m; but by 1995 it has eroded to +5.5 m. The rate of displacement during 1996-1997 is considerably higher than the period of 1964-1995.

The comparison between the results of the control surveying, river channel topology and erosion survey shows the following situation. The rate of the toe recession obtained for the convex part of the landslide toe (limited to hubs R7, 16, 15A, 22) is high compared to the other parts of the toe. This is consistent with the results of the hydrographic investigations carried out for the river channel topology study.

Meanwhile, the river channel topology results indicate that the river channel wall is steeper between Profiles D-3 and D-4 (Fig. 3.3). These profiles limit the same convex part of the landslide toe as shown through the control surveying results to have the highest rate of movement into the river.

The convex segment of the landslide toe has the highest rate of displacement of the displaced mass compared to the other parts of the landslide toe. Also the channel wall is steeper and the North Saskatchewan River thalweg is considerably closer to the south bank along this segment. Therefore, it is concluded that either the scouring phenomenon along the segment has caused a higher displacement rate for the displaced mass; or the higher displacement rate has produced a steeper channel wall along that segment.

It is also evident that the G series of standpipes has moved in a direction very different from that of the hubs, NE rather than NW.

The plunges of the displacement vectors obtained for hubs and standpipes can be classified into two groups. One group includes vectors of hubs located in the accumulation zone of the landslide having plunges of 1 ° to 18° downward. Another group consists of displacement vectors of standpipes having plunges up to 55° downward. The first group of plunges is for the hubs located at the landslide tip (central convex part of the toe).

The plunges of the displacement vectors of hubs vary considerably even among themselves, therefore, the displacement pattern for the sliding mass on the landslide toe is not just translation. It also involves distortion of the mass as indicated by the different values of the plunges of the displacement vectors.

## 5.2 – MENSURATION OF AERIAL PHOTOGRAPHS

### 5.2.1 – Introduction

The aerial photo study was undertaken to carry out a temporal comparative analysis This section explains mensuration as the quantitative approach of the aerial photo study. . Its objectives are to determine the interchangeable dynamic activities of the landslides and the river.The qualitative approach, aerial photo interpretation, will be discussed in the next section (Sec. 5.3). The aerial photos used for both approaches have a scale of ~1/5000. See Appendix A for the aerial photo information.

The work was carried out by T. J. Thomson in 1995. The main objective was to determine the movement of the south and north river edges. This study was limited to the vicinity of the Lesueur landslide starting from 200 m west of the mid point of the Lesueur landslide toe to 200 m east of that. The south and north edges of the North Saskatchewan River have been measured along 7 profiles, T-1 to T- 7, Fig. 5.4.

The following is the presentation of the data that have been processed from the mensuration results, originally carried out by T. J. Thomson in 1995.

### 5.2.2 - Results

The results of the previous mensuration are shown in Figs. 5.5 to 5.11. See Fig. 5.4 for the location map of the profiles.

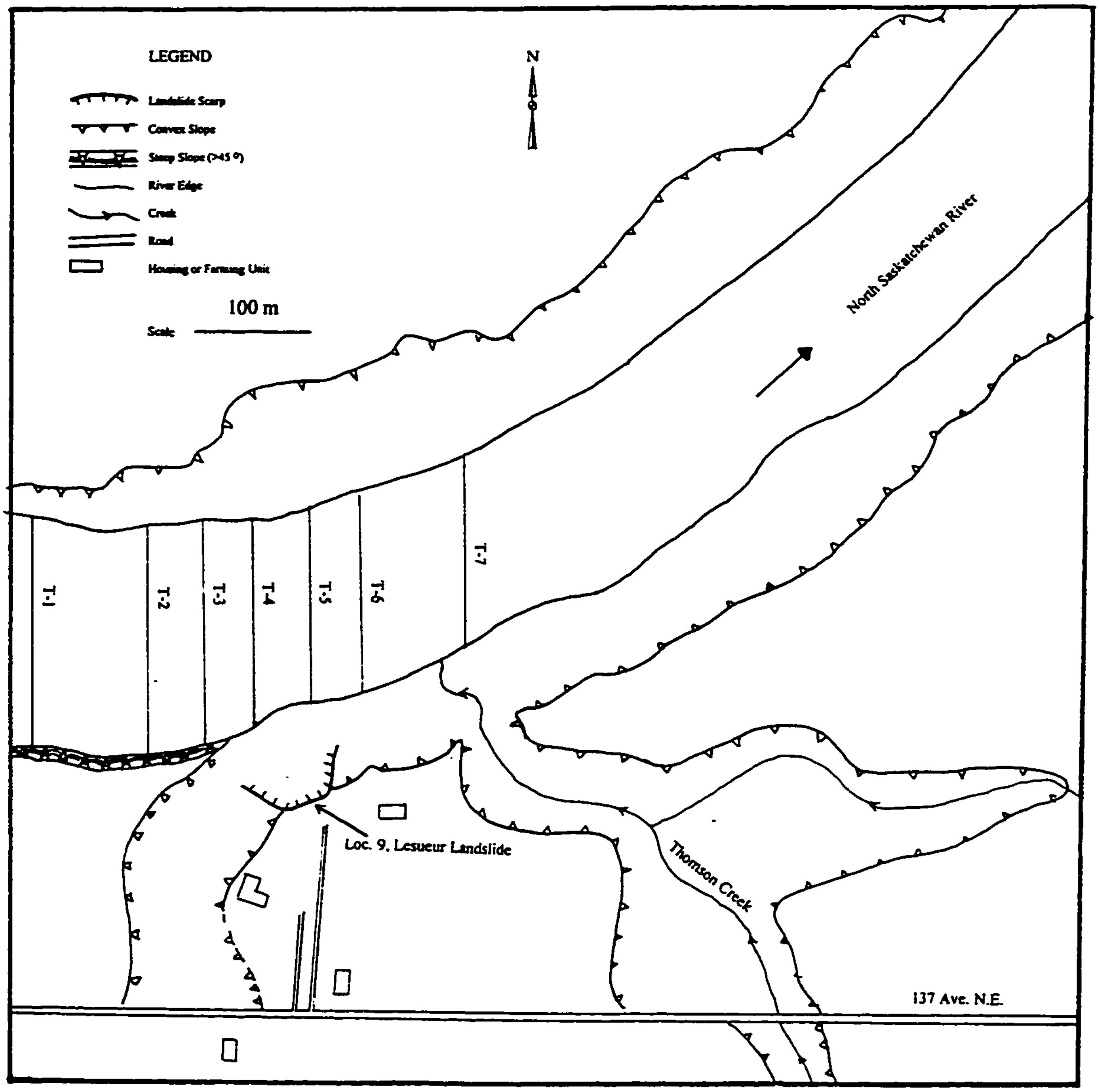



Fig. 5.4 - Location map for the mensuration by T.J. Thomson (1995), showing the directions and locations where the movements of the south and north river edges have been measured through the period 1982 - 1995

*Fig. 5.5 - Movements of South and North River Edges of the N. S. River Versus Time, Profile T- 1*

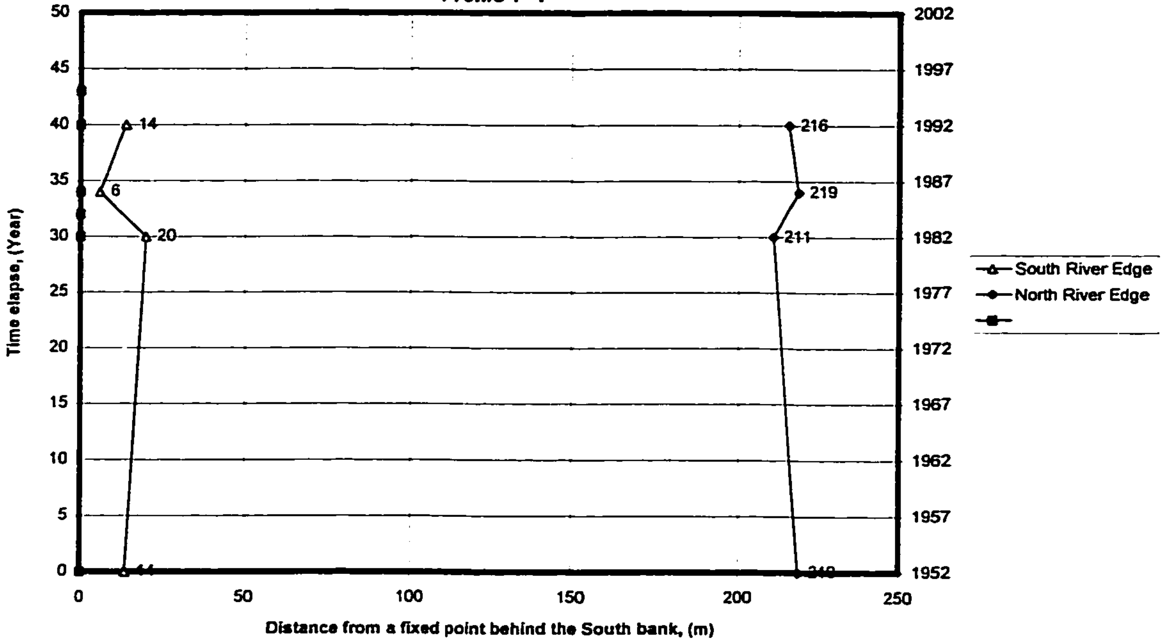



*Fig. 5.6 - Movements of South and North River Edges of the N. S. River Versus Time, Profile T-2*

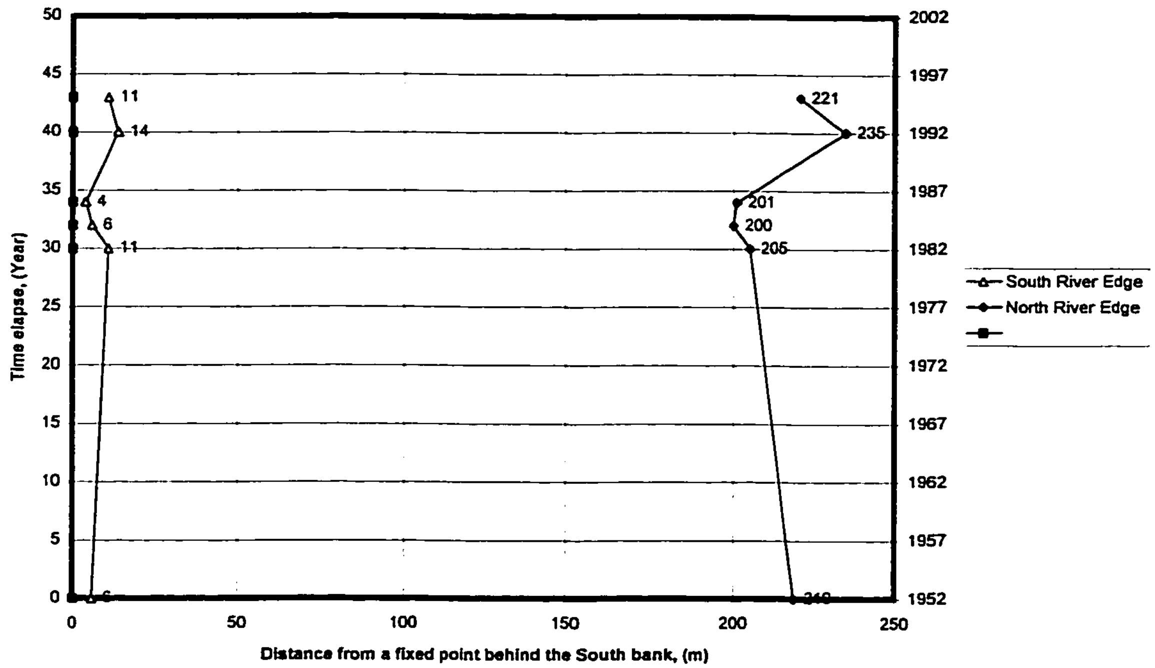


*Fig. 5.7 - Movements of South and North River Edges of the N. S. River Versus Time, Profileat T- 3*

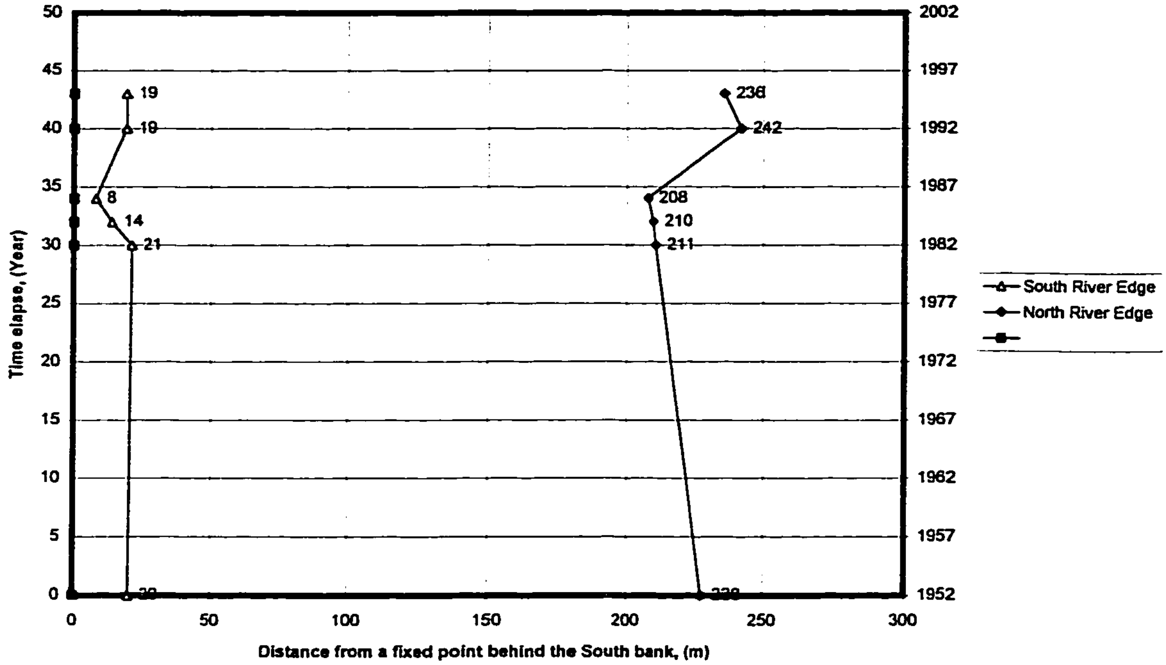



*Fig. 5.8 - Movements of South and North River Edges of the N. S. River Versus Time, Profile at T- 4*

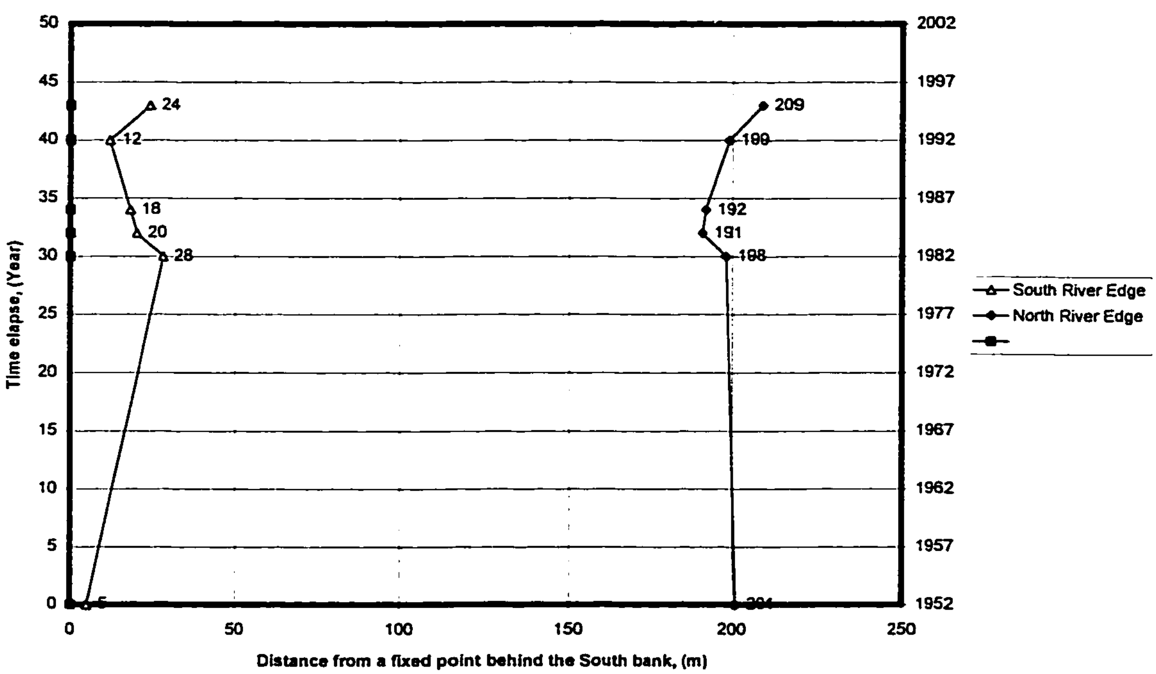


*Fig. 5.9 - Movements of South and North River Edges of the N. S. River Versus Time, Profile T- 5*

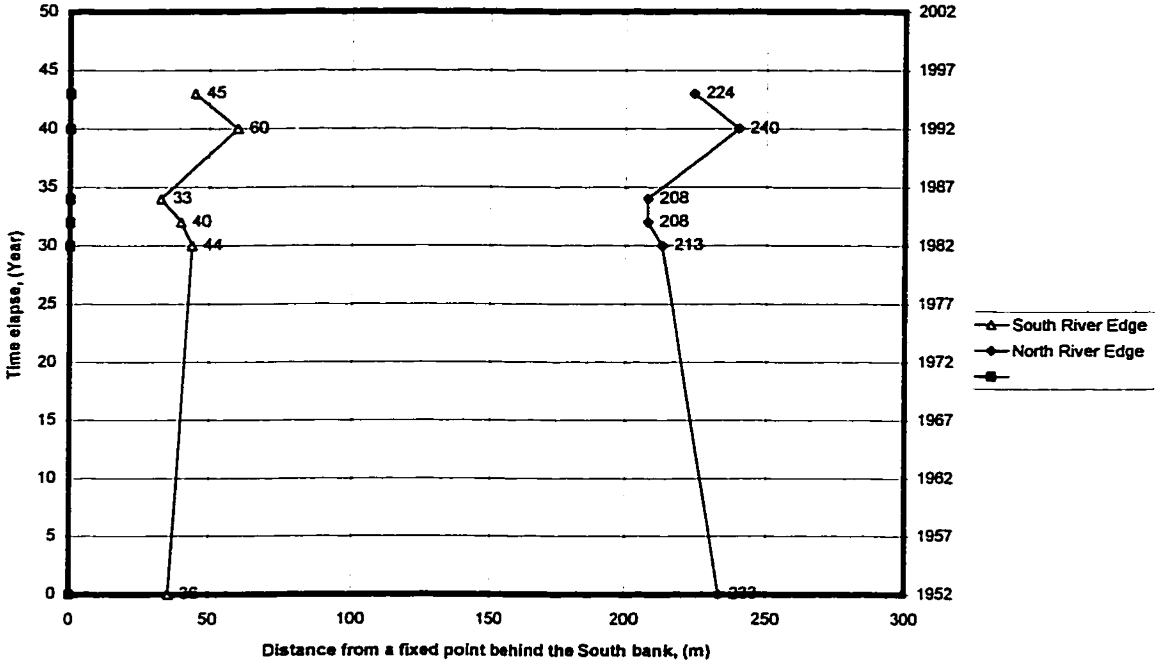



*Fig. 5.10 - Movements of South and North River Edges of the N. S. River Versus Time, Profile T- 6*

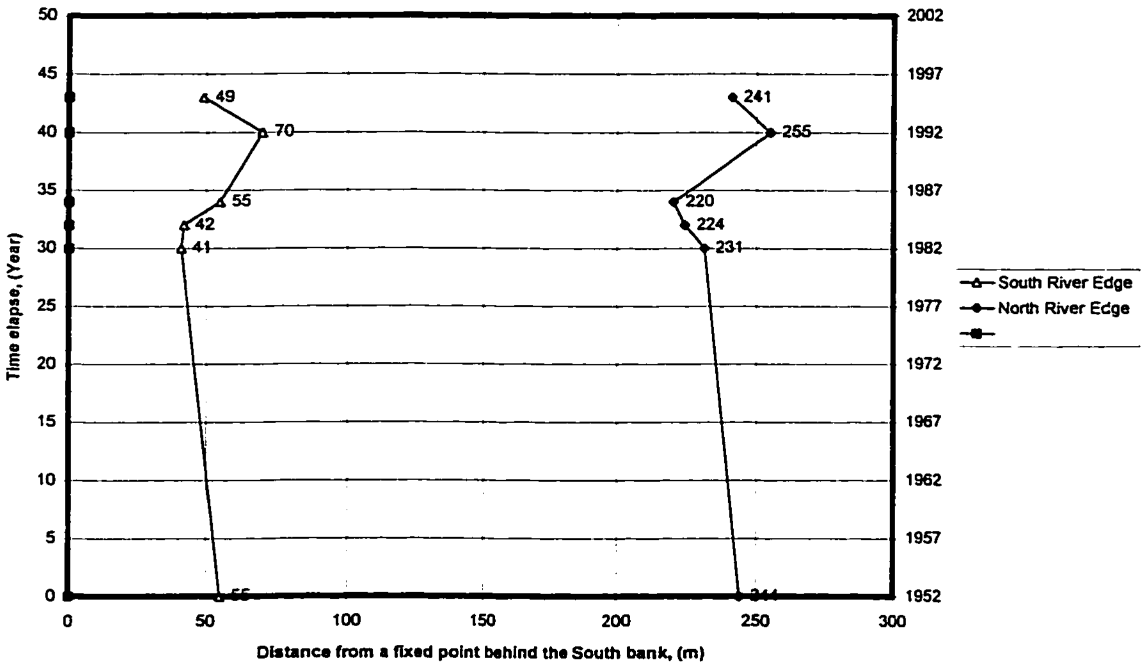
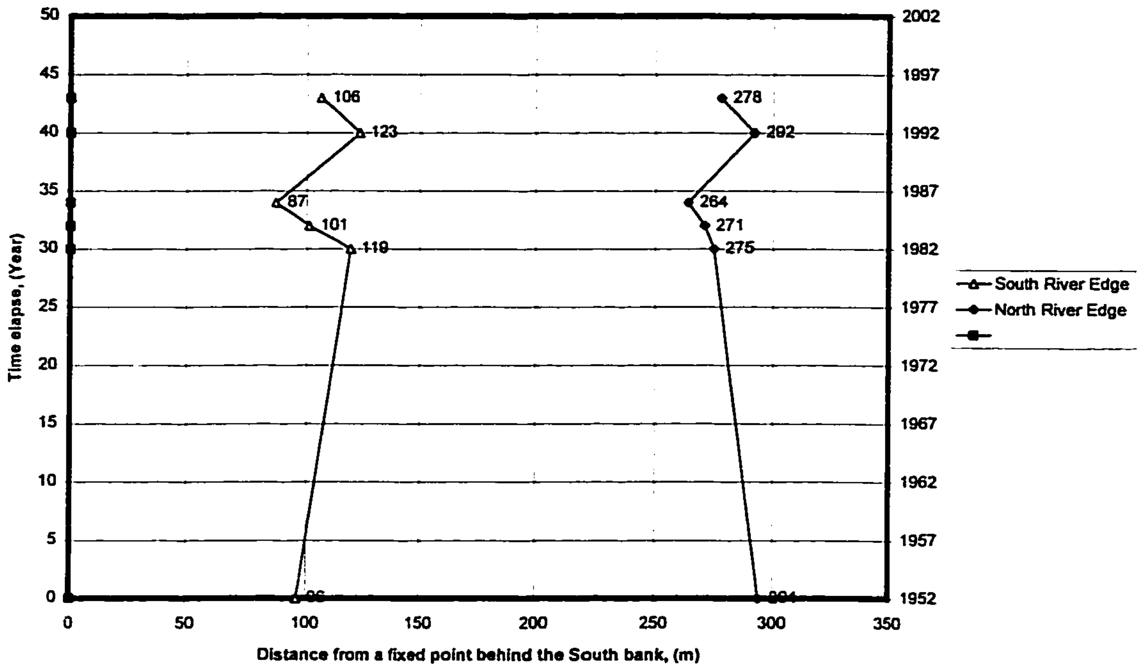


*Fig. 5.11 - Movements of South and North River Edges of the N. S. River Versus Time, Profile T- 7*




According to the graphs of the previous work on mensuration, the river edge displacement over a period 1982-1995 shows the following dynamic regime for the North Saskatchewan River in the vicinity of the Lesueur landslide, Loc. 9 (Table 5.4).

Table 5.4 – River regime interpreted from mensuration

| | ***South River Edge Movement*** | | ***North River Edge Movement*** | | ***Overall River Migration*** | |
|---|---|---|---|---|---|---|
| ***Period*** | ***River Erosion (m)*** | ***River Recession (m)*** | ***River Recession (m)*** | ***River Erosion (m)*** | ***To South Bank*** | ***To North Bank*** |
| **1992-1995** | 14 | | 12.4 | | X | |
| **Profiles have been averaged** | all except T1 and T4 | | all except T4 | | | |
| **1986-1992** | | 17.4 | | 28.3 | | X |
| **Profiles have been averaged** | | all except T4 | | all except T4 | | |
| **1982-1986** | 14.5 | | 6.6 | | X | |
| **Profiles have been averaged** | all | | all except T1 | | | |

As there are errors associated with mensuration results, Table 5.4 is modified to the following schematic diagram, Fig. 5.12, for the south bank, which disregards the magnitude of river erosion or recession.

Also, based on the graphs in Fig. 5.5 to 5.11 another type of graph, river width change versus time, can be drawn (Figs. 5.13 a and b).

Fig. 5.12 - Schematic illustration of the periodic N.orth Saskatchewan River erosion or recession, obtained by mensuration (1995), limited to the vicinity of the Lesueur landslide, through the profiles T-1, to T- 7. As data are limited to 1982-1995, the dashed lines show the probable extensions.

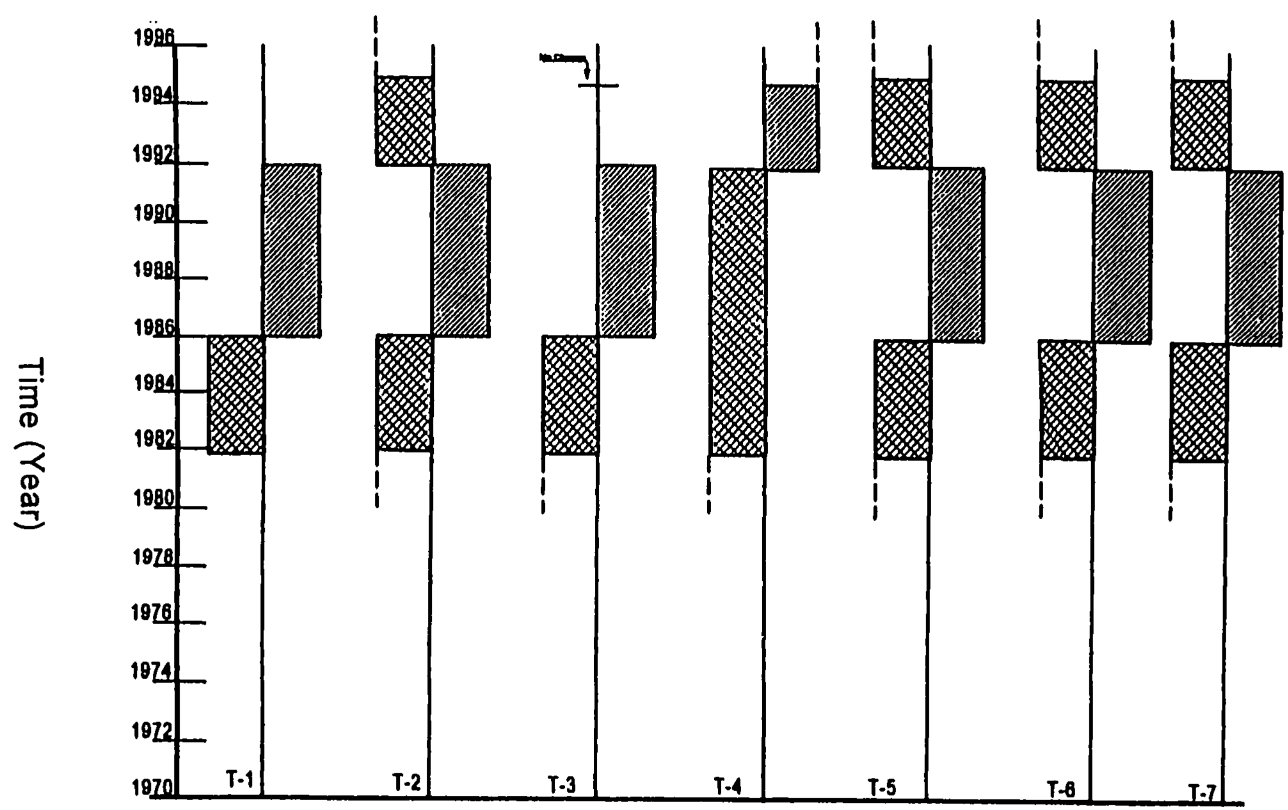


*Fig. 5.13 (a) - N.S. River Width Changes during Time, in vicinity of the Lesueur landslide, ( T-1, T-2 &T-3)*

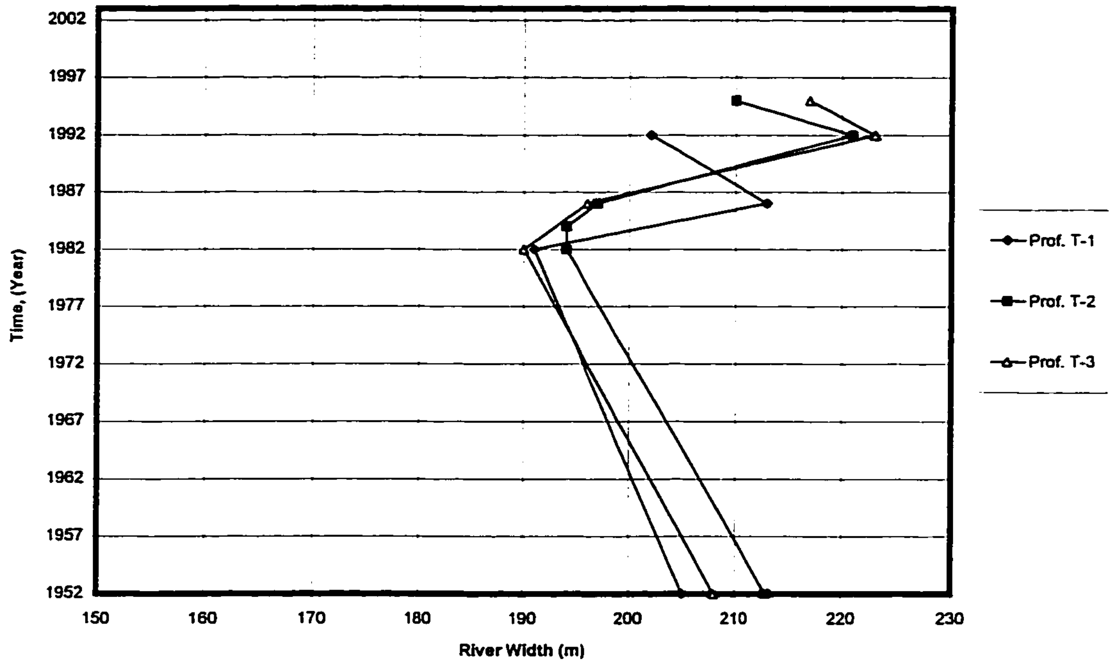
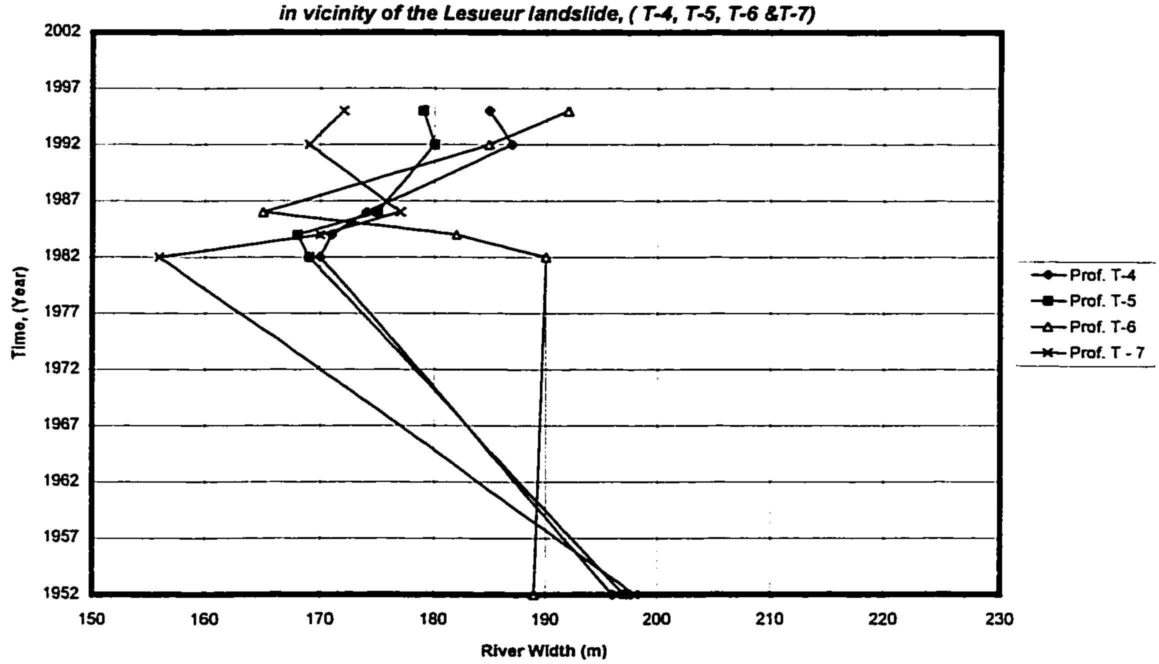



*Fig. 5.13(b) - N.S. River Width Change during Time, in vicinity of the Lesueur landslide, ( T-4, T-5, T-6 &T-7)*



### 5.2.3 - Discussion and Conclusion

The previous study on mensuration by T. J. Thomson (1995) shows the following trend for the North Saskatchewan River regime. See Fig. 5.12.

From 1982 until 1986, it was a period of river erosion at the south (right) bank. Between 1986 and 1992, it was river recession at the south bank. From 1992 to 1995, again has been a period of river erosion at the south bank.

Based on the preceding mensuration results, the south bank of the North Saskatchewan River limited to the studied area, is presently experiencing river erosion, which started in 1992. This helps interpreting the results of the control surveying (Sec. 5.1.3). Thus, the overall toe advance of the landslide at Loc.9 indicated by the control surveying study to be +5.5 m from 1964-1995, had been greater, as a portion of that has been removed by the river erosion indicated by the mensuration study.

Considering the graphs in Figs. 5.13 a and b, it seems that the main process behind the river erosion and recession is not water level fluctuation but is river channel migration. That is concluded as the temporal changes of the river widths show the following trends: for instance, between 1986 and 1992 the south river edge was receding but the river widths at the vicinity of the Loc.9 did not decrease (Figs. 5.13 a and b). Thus, the river recession did not result from a drop in water level. In addition, between 1992-1995, a period of river erosion at the south bank, the river widths did not increase . This shows that river erosion and recession were not produced by increasing discharge and consequent water level rise. Hence, the main mechanism behind the river erosion and recession is the channel migration rather than the water level fluctuations.

## 5.3 - AERIAL PHOTO INTERPRETATION

### 5.3.1 – Objectives and Procedure

The qualitative part of the aerial photo study, the aerial photo interpretation, was undertaken to determine the temporal and spatial distributions of the slope movements along both landslide successions.

The locations introduced in Sec. 5.3.2 have distinctive landslides and have been chosen to show the slope movements along the landslide successions through the period of 45 years. See Figs. 2.4 and 2.5 for the map of these locations.

In order to interpret the landslides, many indicators were used as criteria to define the status of the slope at the time. The words used to describe the intensity of the indicators are shown in Table 5.5.

Table 5.5 - Words Describing the indicators used as criteria to explain the stability status of the mass.

| ***Indicator*** | ***Status*** | | | | |
|---|---|---|---|---|---|
| **Tree Inclination** | Chaos | | Highly inclined | Slightly inclined | Upright |
| **Vegetation** | Bare | | Slightly (re)vegetated | Mod. (re) vegetated | Highly (re)vegetated |
| **Scarp** | Exists | Has appeared or has receded | Slightly (re)vegetated | Moderately (re)vegetated | Highly (re)vegetated |
| **Transverse Horst** | Exists | has appeared or has grown | Slightly shrunk moved downslope | Mod. shrunk moved downslope | Highly shrunk moved downslope |
| **Displaced Debris** | Exists | Has been added or freshly dumped | Modified | Adjusted | Removed |
| **River Edge Convexity** | Highly convex | | Moderately convex | Slightly convex | Straight |

Two things about horsts should be noted here. They are not uplifted blocks and only have been moved downward less than their neighboring blocks. The position of transverse horst mentioned as an indicator can change through time and move from the upslope part of the accumulation zone to its downslope part. Through time, the transverse horsts can shrink and move downward. It seems that the closer they are to the landslide toe, the smaller (thinner and shorter) they are. When a landslide reactivates it seems that they grow in height, such as at locations 13 and 14.

While describing the results obtained from the aerial photo interpretation in the following paragraphs, some of the epochs have been marked with the star sign, ( * ). Those epochs have been specified as it seems that the slopes have experienced a significant change during these phases. Either a landslide happened during that time or an existing landslide was reactivated.

## 5.3.2 – Observations and Results

### Loc. 9

#### Trees

Before 1952: upright
1952 –1962 : no change
1962- 1969 : the tree situation has become chaotic
* 1969-1974 : no change
1974- 1976 : trees situation started to return back to normal but still they are highly inclined.
1976-1980 : they have become slightly inclined.
1980- 1982 : upright
1982-1997 : no change

#### Vegetation

Before 1952: it is highly revegetated.
1952- 1962: Tree clearance has been performed at upland around the Lesueur house
*1962- 1969 : it becomes bare
1969-1971 : no change
1971-1974 : slightly revegetated
1974-1976 : moderately revegetated
1976-1980 : no change
1980-1982 : highly revegetated
1982-1992 : no change
1992-1997 : the bare area at the toe has increased because of the shallow movements at the toe

#### Scarp ( and its talus slope)

Before 1952: it (the scarp of the old landslide) is highly revegetated
1952- 1962 : no change
*1962- 1969 : a fresh scarp has appeared
1969-1980 : no change
1980-1982 : slightly revegetated
1982-1984 : moderately revegetated
1984-1986 : no change
1986-1988 : highly vegetated
1988-1992 : no change
1992-1995 : receded
1995-1997 : receded

‣ **Transverse Horst**

Before 1952 : not exist
1952- 1962 : no change
1962- 1969 : appeared
1969-1971 : slightly shrunk
1971-1974 : no change
1974-1976 : moderately shrunk
1976-1980 : highly shrunk
1980-1997 : no change

‣ **Displaced Debris and the River Edge Convexity**

Before 1952 : debris does not exist but the river bank is slightly convex
1952- 1962 : no change
*1962- 1969 : they are freshly dumped and the river bank is highly convex
1969-1974 : no change
1974-1976 : the debris dump are modified and the river bank is still highly convex
1976-1980 : the debris dump is adjusted and the river bank becomes moderately convex
1980-1982 : the river bank becomes slightly convex
1982-1992 : no change
1992-1995 : new debris have been added and the river bank becomes again moderately convex
1995-1997 : debris has been added slightly

***Loc 11***

‣ **Tree**

Before 1952 : upright
1952- 1962 : no change
*1962- 1971 : they are highly inclined
1971-1974 : they are slightly inclined
1974-1976 : no change
1976-1980 : the situation of the trees has become chaos because of the landslide occurring at the lower half of the mass
1980-1982 : slightly inclined
1982-1984 : upright
1984-1997 : no change

- **Vegetation**

Before 1952: it is highly vegetated
1952- 1962: no change
*1962- 1971: the mass has become partly bare
1971-1974: the mass is slightly revegatated
1974-1976: it is moderately revegetated
1976-1980: the lower half of the landslide is partly bare
1980-1982 : the mass of the lower half has become slightly revegetated
1982-1984: it is moderately revegetated
1984-1988: no change
1988-1990: it becomes highly revegetated except the main scarp
1990-1995: no change
1995-1997: the toe area becomes partly bare

- **Scarp ( and its talus slope)**

Before 1952: it does not exist
1952- 1962: no change
*1962- 1971: exists
1971-1976: no change
1976-1980: a minor scarp is produced in replacement of the transverse horst that has been disappeared
1982-1990: no change
1990-1992: main scarp and the minor scarp are slightly revegetated
1992-1995: main scarp and the minor scarp are moderately revegetated
1995-1997: they are highly revegetated

- **Transverse Horst**

Before 1952: not exist
1952- 1962: no change
1962- 1971: exists
1971-1974 : no change
1974-1976 : it slightly shrunk
1976-1980: it disappeared and was replaced by a small slide at the lower half of the slide
1980-1997: no change

‣ **Displaced Debris and the River Edge Convexity**

Before 1952: not exist
1952- 1962: no change
*1962- 1971: they are freshly dumped but slightly convex
1971-1974: they are modified and the river edge is straight
1974-1976: no change
1976-1980: new debris has been added and part of the river bank is highly convex
1980-1982: no change
1982-1984: the newly dumped debris have been adjusted
1984-1995: no change
1995-1997: they were removed and the river is straight

## *LOC. 13*

‣ **Tree**

Before 1952: upright, but it is visible that this area has already experienced a landslide
1952- 1988: no change
*1988-1990: the trees is chaos
1990-1995: no change
1995-1997: slightly inclined

‣ **Vegetation**

Before 1952: it is highly revegetated
1952- 1971: no change
1971-1974: a shallow movement happened at the toe and it has become bare
1974-1982: no change
1982-1984: the toe is moderately revegetated
1984-1988: no change
1988-1990: the displaced mass is still bare
1990-1995: the bare area has become larger
1995-1997: the bare area has become slightly revegetated

‣ **Scarps (and its talus slope)**

Before 1952: it is highly revegetated
1952- 1988: no change
*1988-1992 : the main scarp has receded
*1992-1995: it has receded
1995-1997: no change

▸ **Transverse Horst**

Before 1952: it did not exist
1952- 1988: no change
1988-1990: exists
1992-1995: it has grown
1995-1997: it slightly shrunk

▸ **Displaced Debris and the River Edge Convexity**

Before 1952: it did not exist
1952- 1980: no change
*1980-1982 : new debris have been added but the river edge is moderately convex
1982-1997: no change

## *Loc. 14*

▸ **Tree**

Before 1952: upright
*1952- 1962; tree situation has become chaos
1962-1971: they are upright again
1971-1995: no change
*1995-1997: the situation at the toe has become chaos

▸ **Vegetation**

Before 1952: it is slightly revegetated
1952- 1962 : some area of the mass has become bare
1962-1971: it has become moderately revegetated
1971-1980: no change
1980-1982 : it is highly vegetated
1982-1992: no change
1992-1995 : the toe area has become bare again
*1995-1997: the bare area has been enlarged

**▸ Scarps (and its talus slope)**

Before 1952: it is moderately revegetated
*1952- 1962: the scarp has receded
1962- 1971: it was slightly revegetated
1971-1974: a minor scarp has appeared as a result of the occurrence of the small slide at the lower half of the landslide and the disappearance of the pressure ridge
1974-1980: no change
1980-1982: the main scarp was moderately revegetated
1982-1986: no change
1986-1988: the main scarp was highly revegetated
1988-1992: no change
1992-1995: the small landslide at the toe seems to be moved slightly again
1995-1997: the minor scarp of the small landslide has been enlarged

**▸ Transverse Horst**

Before 1952: it already existed
*1952- 1962 : it grew because the landslide had already existed at this location and it has only been reactivated
1962- 1971: it moderately shrunk and was revegatated
1971-1974 : it disappeared and was replaced by minor scarp separating the lower half of the landslide from the upper part
1974-1997: no change

**▸ Displaced Debris and the River Edge Convexity**

Before 1952: the debris that already been dumped have adjusted and the river edge is slightly convex
*1952- 1962: new debris has been freshly dumped and the river bank is highly convex
1962- 1971: the debris have been modified and the river edge is moderately convex
1971-1974: no debris being added but the river bank has become highly convex
1974-1984: no change
1984-1986: debris have been adjusted and the river edge has become slightly convex
1986-1990: it was adjusted more
1992-1995: new material has been added and the river edge was composed of two curved parts
1995-1997 no change

### ⍀ Loc. 27

**‣ Tree**

The area covered by this landslide is small and inclination of trees is not visible.

**‣ Vegetation**

Before 1962: it is highly vegetated
1962-1974: it is partially bare either at upper part of the slope or lower part
*1974-1976: the bare area has been enlarged
1976-1980: no change
1980-1982: it is moderately vegetated (revegetated as it was bare before)
1982-1986: it is highly vegetated
1986-1993: it is partially bare, especially at the upper part of the slope
1993-1997: the bare area at the middle part of the slope has been enlarged

**‣ Scarp (and its talus slope)**

Before 1971: not exist
*1971-1974: it is visible at elevation lower than the upland, however, not clearly.
*1974-1976: it is more visible and has receded
1976-1984: it is vegetated (revegetated)
1984-1995: it seems that it has receded (landslide reactivated) as many segments of that have joined together and produced 3 larger segments comprising the scarp.
1995-1997: it is vegetated

**‣ Displaced Debris and the River Edge Convexity**

Before 1971: none
*1971-1974: river edge becomes moderately convex and some debris have been dumped
1974-1976: river edge is not convex while volume of debris have increased
1976-1986: displaced debris have been adjusted
1986-1990: the river edge has become straight
1990-1997: no change

### ⍀ *Loc. 38*

**‣ Trees**

Before 1971: upright
1971-1974: no change
1974-1976: they were slightly inclined

1976-1992: no change
*1992-1995: the situation is chaos
1995-1997: no change

**Vegetation**

Before 1971: it was highly vegetated
1971-1974 : the lower half of the landslide became bare because of the shallow movements occurrence at the toe
1974-1976: the bare area has been enlarged
1976-1992 : no change
1992-1995 : almost the entire mass area became bare
1995-1997 : the bare area has been enlarged

**Scarps ( and its talus slope)**

Before 1971 it did not exist
1971-1974: no change
1974-1976: the shallow movement at the lower half was reactivated and move backward which has displaced more material
1976-1990: no change
1990-1992 : again the minor landslide at the lower half was reactivated and moved backwards
*1992-1995 : the shallow movement has moved backwards drastically and occupied almost the entire mass. This backward movement has led to production of a main scarp which is located at the upland elevation
1995-1997 no change

**Transverse Horst**

Before 1971: it did not exist and it was not produced later through the time

**Displaced Debris and the River Edge Convexity**

Before 1971: not exist
1971-1974 : the debris have been removed and river edge is straight
1974-1990: no change
1990- 1992 : displaced debris have been freshly dumped and the river edge is highly convex
*1992-1995 : new debris have been added and the river edge is moderately concave
1995-1997 : again new debris have been added and the river edge has become highly convex

**Temporal and spatial distribution of the landslides**

Based on all of the preceding interpretations, Table 5.6 summarizes the major slope movements between 1952-1997.

Table 5.6 - Temporal and spatial distribution of the Landslides, either initiated or reactivated, for the entire succession

| **Landslide Initiated** | | **Landslide Reactivated** | |
|---|---|---|---|
| **Location** | **Epoch or Year** | **Location** | **Epoch** |
| Loc.13 | Before 1952 | Loc. 27 | 1974-1976 |
| Loc. 14 | 1952-1962 | Loc. 13 | 1988-1990 |
| Loc. 9 | 1963 | Loc. 9 | 1992-1997 |
| Loc. 11 | 1964 | Loc. 27 | 1992-1995 |
| Loc. 27 | 1971-1974 | Loc. 38 | 1992-1995 |
| Loc. 38 | 1971-1974 | Loc. 14 | 1995-1997 |

The above table can also be represented as follows in order to emphases the periodic movement of the landslides, Table 5.7.

Table 5.7 - Periodic movement of the landslide along the Lesueur succession, showing period of initiations and periods of reactivation

| | | | | | | |
|---|---|---|---|---|---|---|
| **1995-1997** | | | Reactivated | | | Reactivated |
| **1992-1995** | Reactivated | Reactivated | | | | Reactivated |
| **1990-1992** | | | | | | |
| **1988-1990** | | | Reactivated | | | |
| **1986-1988** | | | | | | |
| **1984-1986** | | Reactivated | | | | |
| **1982-1984** | | | | | | |
| **1980-1982** | | | | | | |
| **1976-1980** | | | | | | |
| **1974-1976** | | Reactivated | | | | |
| **1971-1974** | Initiated | Initiated | | | | |
| **1962-1971** | | | | | Initiated | Initiated |
| **1952-1962** | | | Initiated | Initiated | | |
| | **Loc.38** | **Loc.27** | **Loc. 14** | **Loc. 13** | **Loc. 11** | **Loc.9** |
| *Time ( Year)* | *Downstream Locations* | | | | | *Upstream Locations* |

### 5.3.3 - Discussion and Conclusions

The influences of human activities on the slope movements can be determined if the results of the landuse study (Sec. 2.3.3) and the aerial photo interpretation (Sec. 5.3.2) are compared. The following are the comparisons between them. In each paragraph, at first the results of the landuse study by a specific aerial photo are introduced and then the results of the aerial photo interpretation are presented. Therefore, the photos that show a temporally relevant event to a landuse change naturally date later than the photo used for identifying that landuse change.

The 1962 photo indicates two main landuse changes. One is a significant dumping of the mining wastes on the north side of the riverbed, exactly opposite the Lesueur landslide location. The other change is that on the upland area of Loc. 9, a distinctive tree clearance took place between 1952 and 1962. Also, the same photo shows that a septic tank existed at this location and many industrial units (plants) have been added to the south of this location, during the same period, 1952-1962. Meanwhile, the1969 photo shows that Loc. 9 has experienced the large Lesueur landslide, whose exact date according to the other records is Sep. 3, 1963.

The 1971 photo displays evidence representing the following changes. Oil pipeline construction upstream of Loc. 9 and north bank gravel pit activity. According to the slope movement monitoring, the only temporally relevant event was slumping of the river bank.

The 1974 photo indicates a development stage for the north bank gravel pit activity, an increase of the Oldman Creek discharge, construction of 4 tanks to the east of Loc.38 and development of the farming and industrial units at Loc. 26 & 27 and Loc.38, respectively. The temporally relevant event, according to the slope movement monitoring, is shown on 1976 photo which indicates an enlargement for the bare area at the middle of the slope of Loc. 27, showing retrogression of that shallow movement.

The 1976 photo shows another development stage for the north bank gravel pit activity, removal of 4 tanks to the east of the Loc.38 and finally the kettles to the southeast of Loc.38 have been leveled and their discharge channel has been disconnected. No event with temporal relevancy was found by the slope movement monitoring study.

The 1980 photo shows the following landuse changes in the area. North bank gravel pit activity has decreased and an open lagoon has been built 570 m southwest of the Loc.9. The farming and industrial units at Loc. 26, Loc. 27 and Loc. 38 have been developed. The 1995 photo, by the aerial photo interpretation, shows that the landslide at Loc.9 had experienced a reactivation at an unknown time between 1992 and 1995, as the bare area of the shallow movement near the landslide toe has increased (advanced), the scarp had receded and the toe concavity had increased. The other change that may have temporal relevancy to this landuse changes is shown by the 1980 photo. This photo shows that the shallow movement at the middle of the Loc. 11 was reactivated between 1976 - 1980.

An important the issue to be noted here, is as follows. In some situations, a temporal relevancy might exist between a landuse change and an event; but no relevancy can be found between those two from point of geological and hydrological processes or geometrical changes. For instance, the landslide reactivation of the Loc.9, sometime after 1992, is relevant to the contemporary open lagoon operation. However, the relevancy of the possible open lagoon leaching and the local groundwater configuration cannot be justified. The groundwater flow direction is not towards the Loc. 9, where the upland elevation is higher.

The 1982 photo shows another stage of development for the north bank gravel pit activity but no temporally relevant event was observed by the slope movement monitoring.

The 1984 photo indicates that the scarp of the Lesueur landslide, Loc.9, had been trimmed, a drainage channel that collects the agricultural waste had been reshaped and connected to the upstream of the Thomson creek, a pond has been insulated by a liner at the upland of Loc. 27 and the kettles to the east of Loc.38 had been removed. The1986 photo from the aerial photo interpretation shows a landslide reactivation at Loc. 27.

The 1986 photo indicates the construction of a pool in the upland area of Loc.9, construction of a power transmission line at the upstream of Loc. 9 and tree clearance to the southwest of Loc. 26. No temporally relevant event was found by the aerial photo interpretations.

The 1988 photo indicates a significant stage of development for the north bank gravel pit activity. No temporally relevant event was observed by the slope movement monitoring study.

The 1993 photo indicates another stage of development for the industrial unit at the upland of the Loc.38. According to the aerial photo interpretation, the 1995 photo displays that the landslide at Loc. 38 had been reactivated sometime between 1993 and 1995. However, the effect of the landuse change on the landslide at Loc.38 can just be accounted as a second degree triggering factor because, as discussed in later sections, after 1992 came a period of reactivation of landslides along the entire succession, and not just Loc. 38.

Dumping mining wastes on the north side of the river between 1952-1962 is considered to be a triggering factors for the landslide occurrence at Loc.9 in 1963 as a result of modification of the river flow pattern. Also, tree clearance at upland area of Loc. 9 during the same period can be a triggering factor. However, for the following cases, the landuse changes can be considered as triggering factors just for the reactivation of the landslides and not their initial occurrences. The development of industrial and farming units at Loc. 27 and Loc.38 have triggered reactivation of the landslide at Loc. 27 between 1974-1976 and 1984-1986, also reactivation of landslide at Loc.38 between 1993-1995.

Comparison between the results of the aerial photo interpretation and mensuration, Tables 5.6 and 5.7 and Fig. 5.12, suggests the following relationship. The period of reactivation for the landslides along the succession obtained from the aerial photo interpretation coincides with the last period of river erosion obtained from mensuration. Therefore, it is suggested that the return of the river erosion period, since 1992 for the North Saskatchewan River, has reactivated many of the landslides along the landslide successions during the past few years. This situation is consistent with the field observations made during the last few years.

Based on Tables 5.6 and 5.7, which represents the spatial and temporal distribution of the landslides along the succession, a relationship can be suggested between the time of landslide occurrence and its location compared to the existing landslides at that time. The landslide at Loc. 14 is just downstream of the landslide at

Loc. 13 (neighboring location). Table 5.6 shows that the time interval for the landslide at Loc. 14 is 1952-1962 while for that at Loc.13 it was before 1952. This relationship also exists between the landslides at Locs. 9 and 11. The landslide at Loc. 11 occurred one year after Loc. 9 (S. Thomson, personal communication). Considering the spatial distribution, Loc. 11 is downstream of Loc. 9 (200 m). This situation is similar to Loc. 14 and Loc. 13. The suggested mechanism behind this relationship could be modification of the river flow pattern downstrream of the landslide location which can be done by the displaced mass blocking the river channel. The following conclusion can be made, consequently.

The occurrence of a landslide can apparently cause modificatoin of the river flow pattern at its downstream. The resulting modification will increase the river erosion (river bank recession) leading to a landslide initiation or reactivation at downstream of the primary landslide.

# Chapter 6 GROUND SURVEYS

# Chapter 6 GROUND SURVEYS

## 6.1 - OBJECTIVES AND PROCEDURE

It is the intent of this chapter to introduce the results of the ground surveys undertaken to determine the external geometry of the slopes. The measurements and observations alllow an estimate of the surface of rupture type and its approximate position by Hutchinson's method (1983).

In order to perform the ground surveys, 18 locations were chosen from the 27 locations investigated previously for stratigraphy along S-S' traverse (Figs. 2.4, 2.5 for location map). Among the 18 locations, 14 locations contain either reactivated or inactive landslides. The landslides at these locations will be grouped later and are as follows, 9, 10, 11, 13, 14, 15, 16, 22, 23, 26, 27, 36, 37 and 38. The other 4 locations either include undisturbed slopes or contain small slope movements and cannot be grouped with the others. The undisturbed slopes have been investigated in order to determine the magnitudes and patterns of deformation for the disturbed slopes, comparatively.

I performed the ground surveys by a compass, level and tape to provide plans and profiles of different locations. The longitudinal profiles were chosen along the steepest slope of the location to pass through the central parts of that location (landslide). The profiles were in the direction of mass movement. Occasionally, two or three profiles have been provided for one location if there was a distinctive feature for that location.

In addition to geometrical measurements, the existence, place or status of the following features for each location (landslide) have been investigated: graben, longitudinal or transverse horst, sharp break in slope, shallow movement, spring or seepage, vegetation (bare to highly vegetated), tree status (age, density, inclination and type), tension crack, sag pond or marsh, landslide relict, toe convexity and river beach materials.

## 6.2 - MEASUREMENTS AND OBSERVATIONS

For each location, a plan and a profile (or profiles) have been provided which are presented at the end of the section that describes the location. The legend for the stratigraphic columns represented in the profiles were introduced in Fig. 4.2. The places of the features observed in the field are shown on profiles and plans. Those that need description are presented in paragraphs preceding the relevant plan and profile. At first, the features that are general for the entire location will be introduced in the paragraphs, for example the existence and place of the transverse horst, transverse sharp break in slope, toe convexity and river beach materials.

The description for each profile will be provided starting from the crest and move downslope. The features described will be in the following order; scarp, talus slope, graben and horst, sharp break in slope, shallow movement, seepage and tension crack. Meanwhile, the vegetation and tree status will be noted for each portion independently if it is relevant to a specific situation. It should be noted again that if a feature needs a description it would be noted. Otherwise, it is shown on the appropriate plan or profile. The following are the 18 locations that have been investigated by the ground surveys.

**Loc. 9**

As shown in Fig. 6.1, three longitudinal profiles have been constructed by the ground surveys for this location. They are P-9A, P-9B and P-9C, from upstream to downstream, respectively. The reason for providing three profiles is the existence of two, almost parallel, longitudinal horsts at those locations. Their trend are in N 50 W to N 60 W directions.

The great amount of tree branches dumped just downslope of the main scarp has prevented the natural slope movement. The transverse horst is located 15 to 20 m horizontally north of the head scarp. Its segments are parallel to the main scarp segments. The long horsts terminate where there is a sharp break in slope which itself contains a shallow movement. The toe between P-9B and P-9C is convex into the river (looking from crown).

At profile P-9A, Fig. 6.2, graben and transverse horst exist on the upslope part of the accumulation zone. At the foot of the landslide where the shallow movement exist, the displaced mass is highly internally deformed and it flows. The tension cracks at the lowermost shallow movement are two sets perpendicular to each other.

For profile P-9B, Fig. 6.3, the existence of the second graben and horsts at the downslope part of the accumulation zone is noticeable. Also, the shallow movement has produced a minor scarp.

Profile P-9C, Fig. 6.4, shows that the slope contains graben and horst but with low relief. It seems that the accumulation zone has been depressed as this profile indicates and the relative elevation differences between graben and horst have decreased. There are shallow movements containing great amount of seepage.

Fig. 6.4(b) represents a fence diagram of the Lesueur landslide, Loc. 9 in order to visualize the situation better.

**Loc. 10**

As is visible from Fig. 6.5, there is no vertical segment for the main scarp for this landslide, profile P-10. The former talus slope, which is vegetated now, plus the accumulation zone, construct a large concave-up part for the slope. No transverse horst is visible at this location but at the lower part of the accumulation zone there is a transverse sharp break in slope.

Fig. 6.1 - Plans of Loc. 9 and Loc. 10

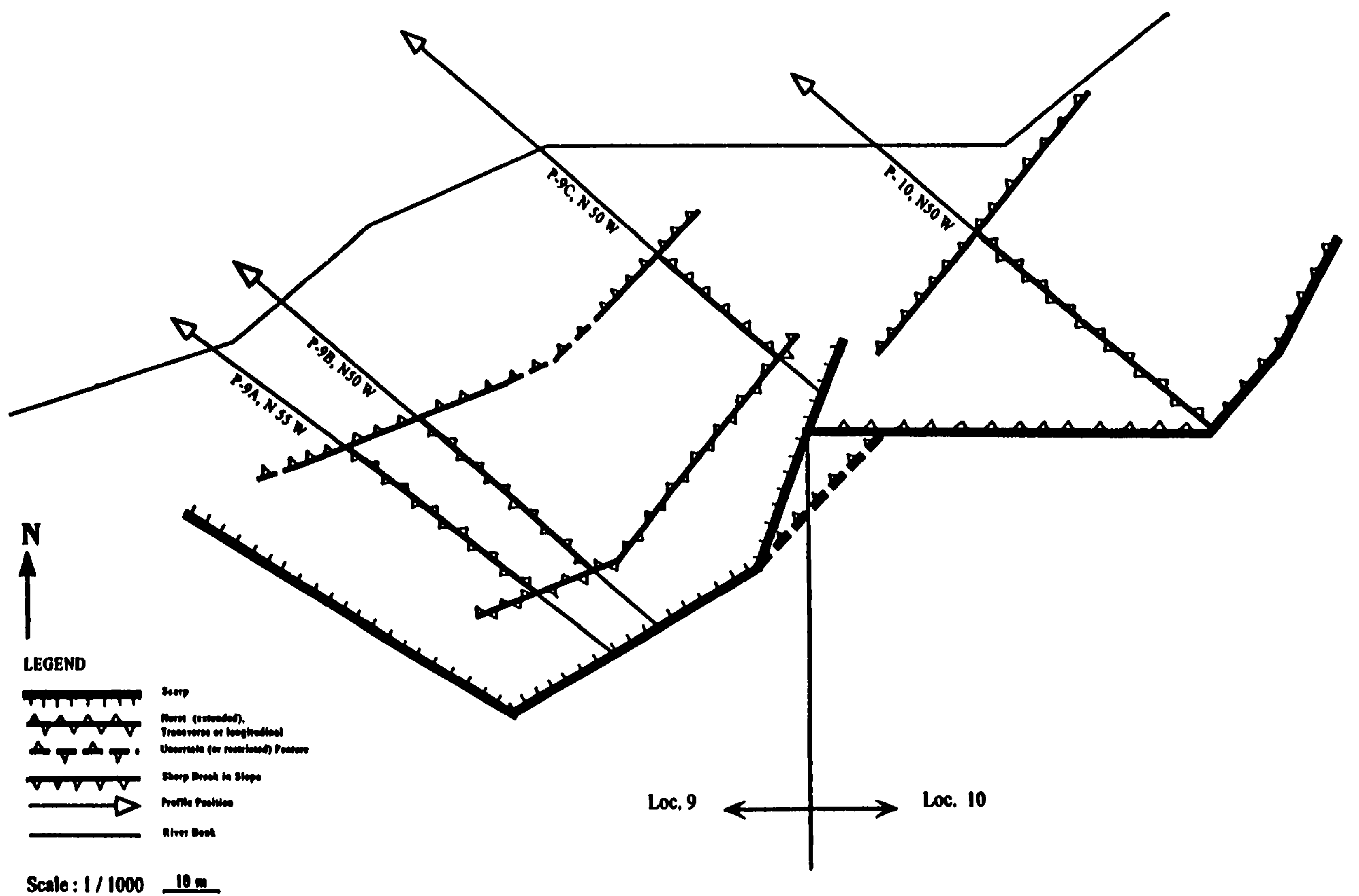


*Fig. 6.2 - Longitudinal Profile (P-9A) of Loc. 9, Lesueur Landslide,*
**(looking downstream)**

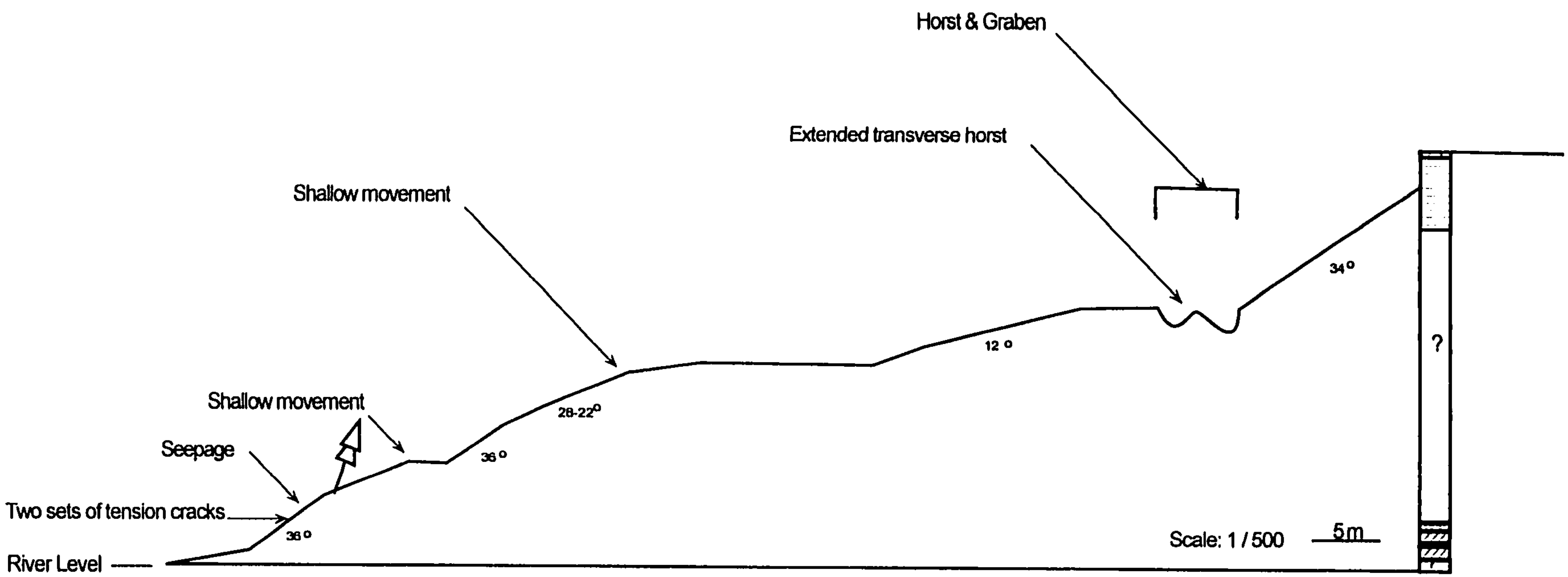


*Fig. 6.3 - Longitudinal Profile (P-9B) of Loc. 9, Lesueur Landslide,*
***(looking downstream)***

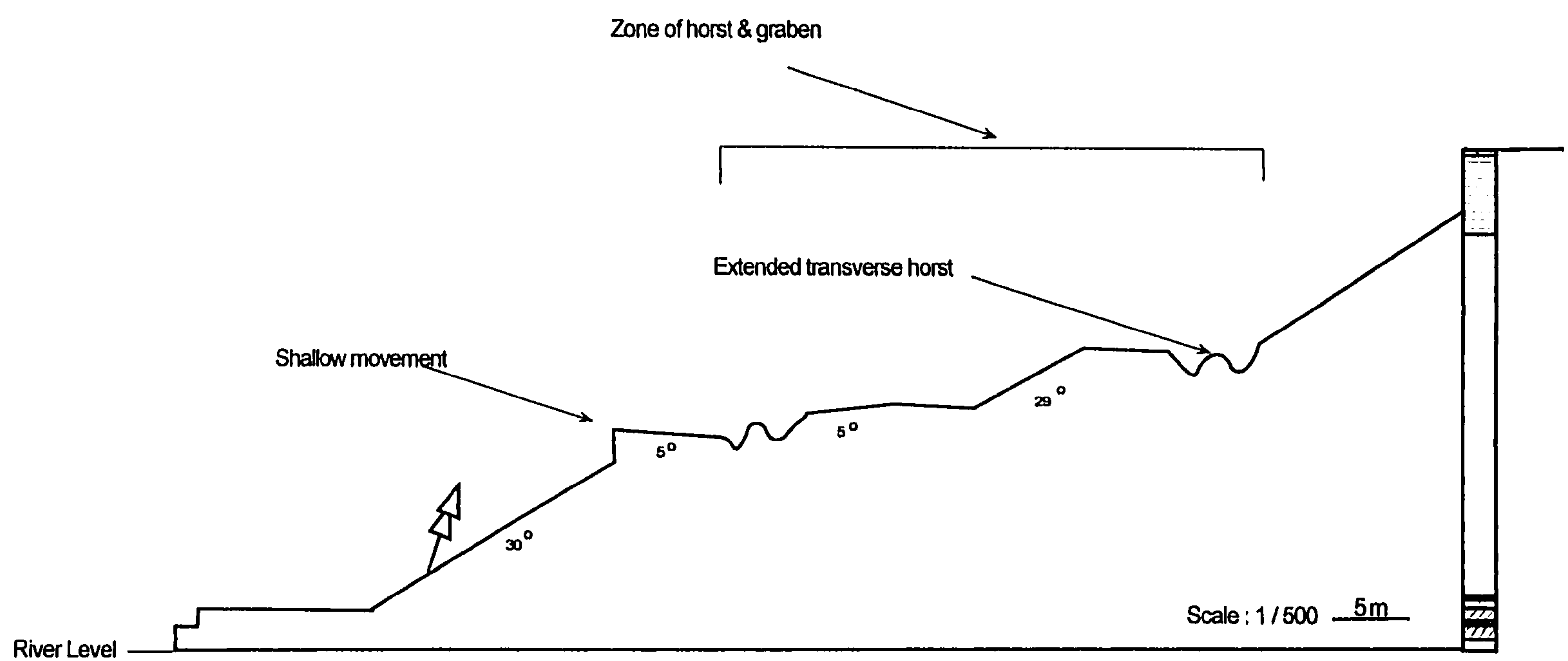


*Fig. 6.4 (a)- Longitudinal Profile (P-9C) of the Loc. 9,* **(looking downstream)**

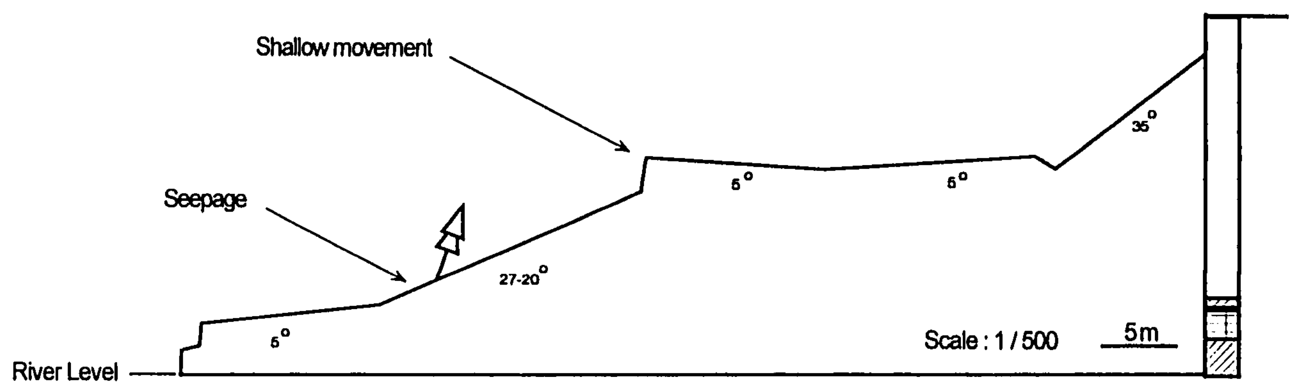
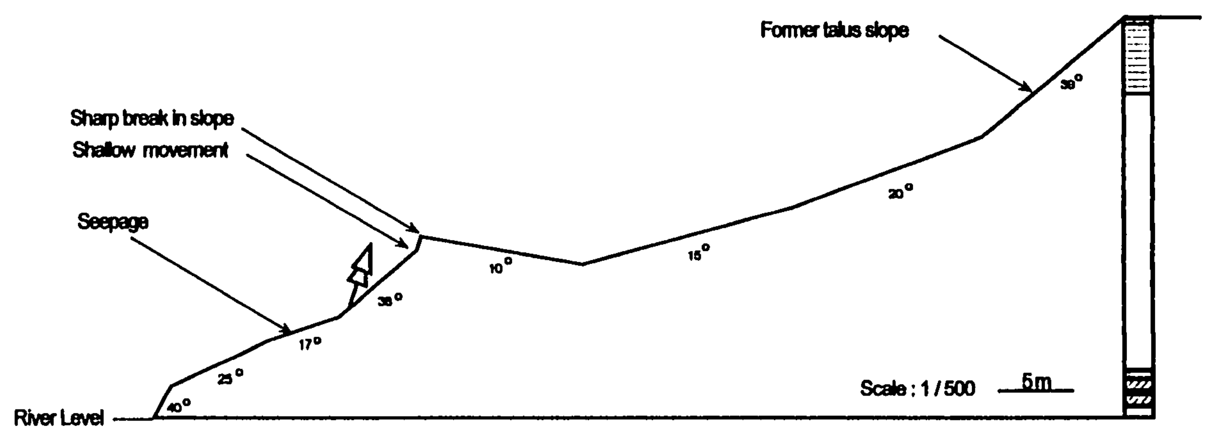


*Fig. 6.4(b) - Fence diagram showing the 3D view of the slope at the Lesueur landslide, (looking downstream)*

*Fig. 6.5 - Longitudinal Profile (P-10) of Loc. 10,* **(looking downstream)**



**Loc. 11**

Fig. 6.6 shows the plan of this location and the direction and position of profile P-11. The downstream (right) part of the main scarp is at a lower elevation compared to the upstream part. The middle segment of the scarp connects them together. The polygon (rectangular) area shown by the star sign (*) in Fig. 6.6 seems to be a landslide relict bounded on the south margin by the scarp of an old landslide and on the north and west margins by the scarp of the recent landslide.

The vegetation on this landslide relict is old trees (spruce) dried up to half of their heights. The downstream part of the landslide toe is covered by trees which are old, dense, dried and inclined upslope. The upstream 70 m of the toe is straight and the river beach is gravel. Downstream of that, the landslide toe becomes concave and the river beach is sand. The next downstream 70 m of the beach is gravel.

Profile P-11, Fig. 6.7, indicates that the upstream segment of the recent landslide scarp has retrogressed by toppling and consequently, there is a talus slope down the main scarp. Along the upslope part of the accumulation zone there are many horsts and grabens. At the downslope part of the accumulation zone there is a transverse sharp break in slope.

Fig. 6.6 - Plan of Loc. 11

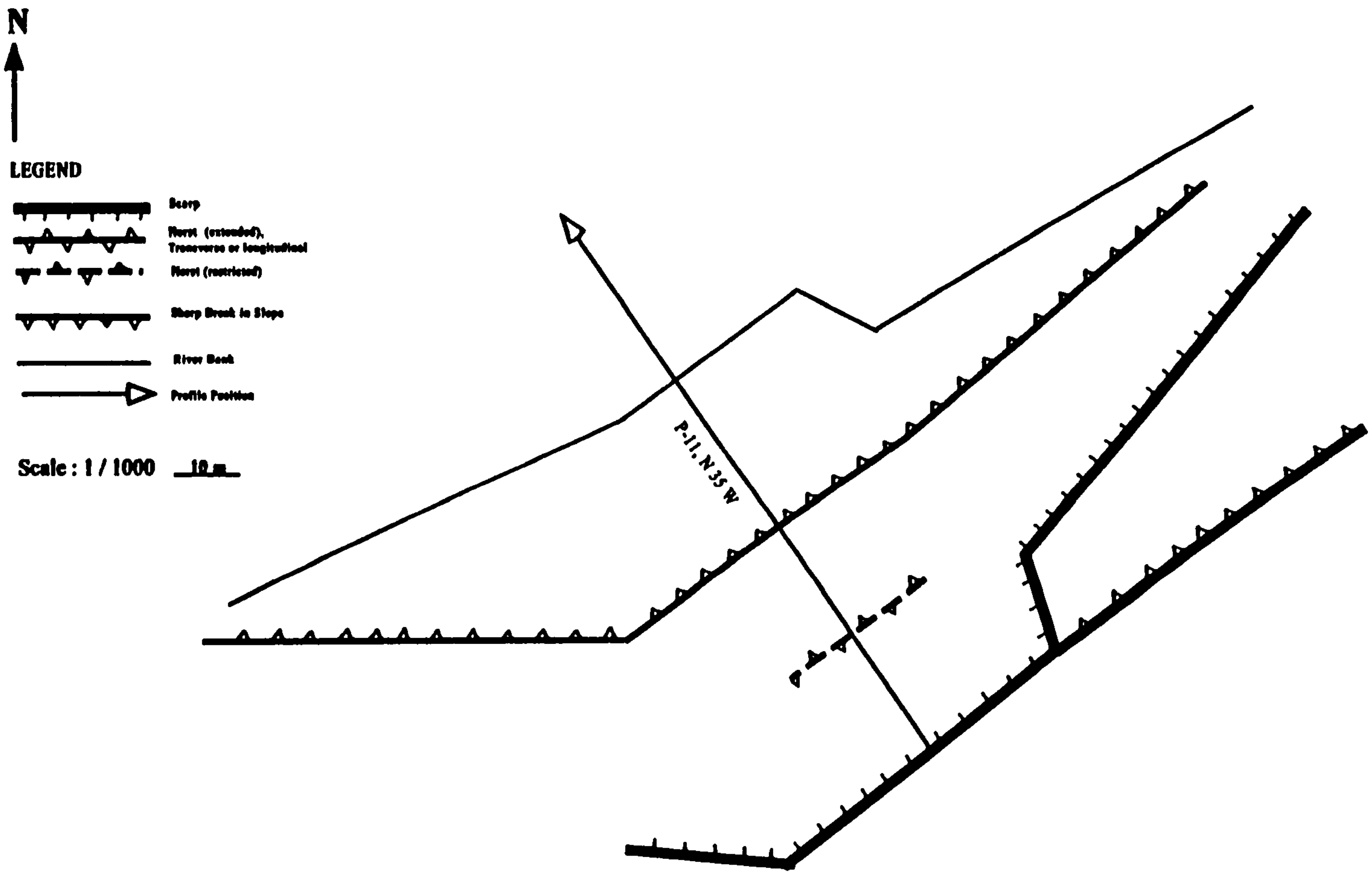
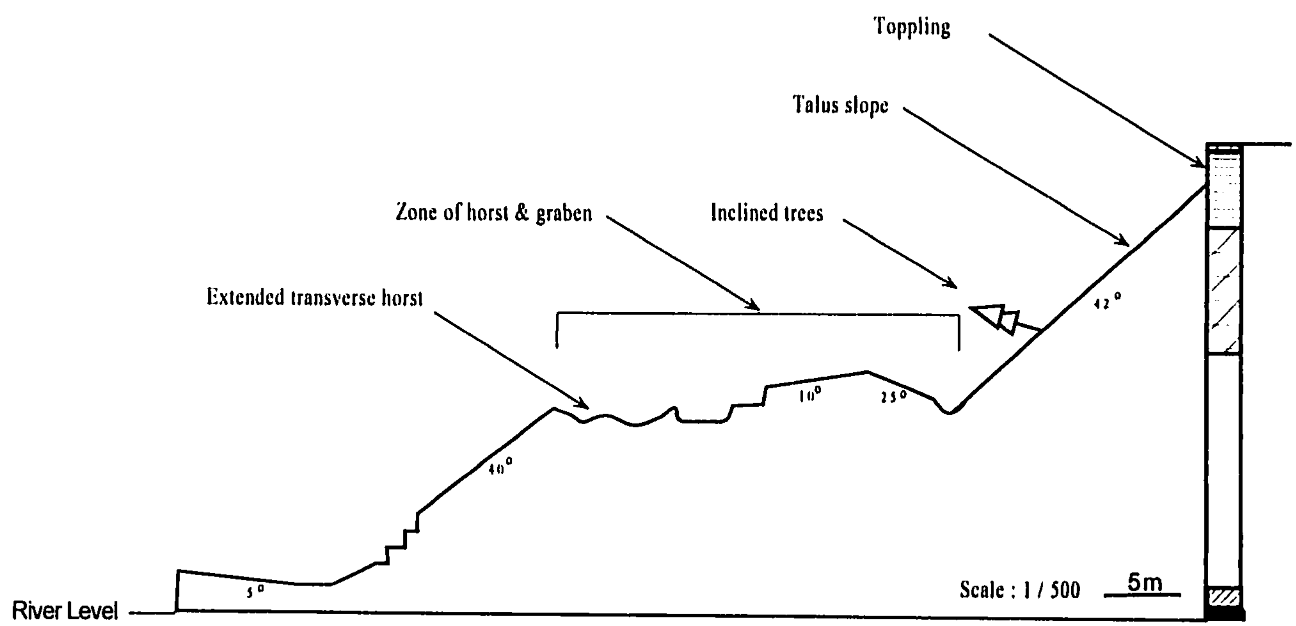


*Fig. 6.7 - Longitudinal Profile (P-11) at Loc. 11,* **(looking downstream)**



**Loc. 13**

The plan of this location, in Fig. 6.8, shows that two profiles have been constructed for this location. The transverse horst is extended almost across the landslide except the downstream side where it changes to a sharp break in slope. There are two landslide relicts at both flanks of the recent landslide at this location.

Profile P-13A, Fig. 6.9, passes through the main scarp of the recent landslide and shows a 4.5 m vertical scarp. The scarp is presently retrogressing by toppling as the toppled block and the trees, which are inclined downslope, are visible. Downslope of the talus slope, there are horsts and grabens.

Profile P-13B, Fig. 6.10, passes through the right flank of the recent landslide, which itself is a relict of an old landslide. The uppermost part of the slope is concave-up and is highly vegetated. Then, there is a small vertical scarp of 1 m high. This scarp is followed by a convex-up part. Downslope of that there is a graben.

*Fig. 6.8 - Plan of Loc. 13*

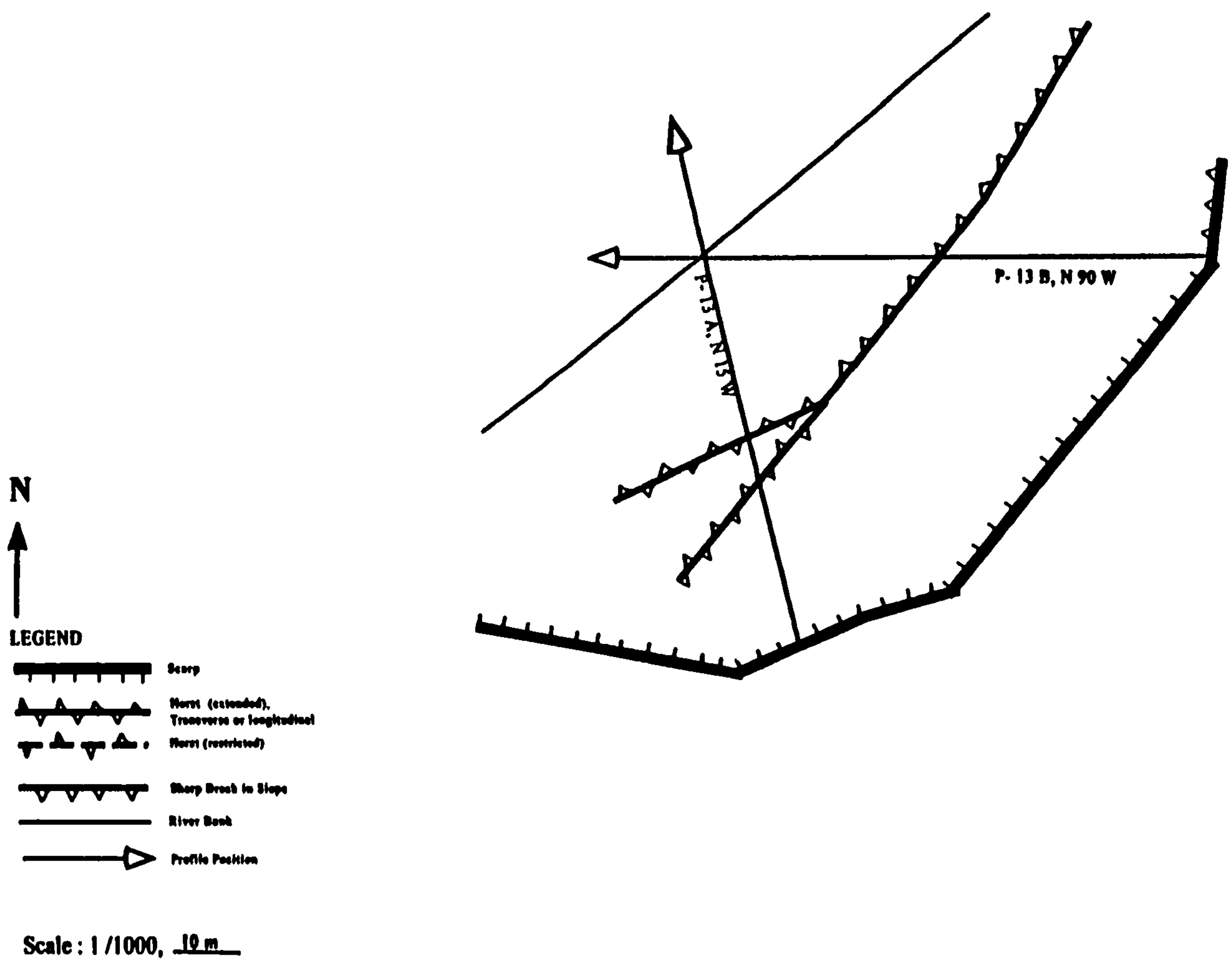


*Fig. 6.9 - Longitudinal Profile, P-13A, at Loc. 13,* ***(looking downstream)***

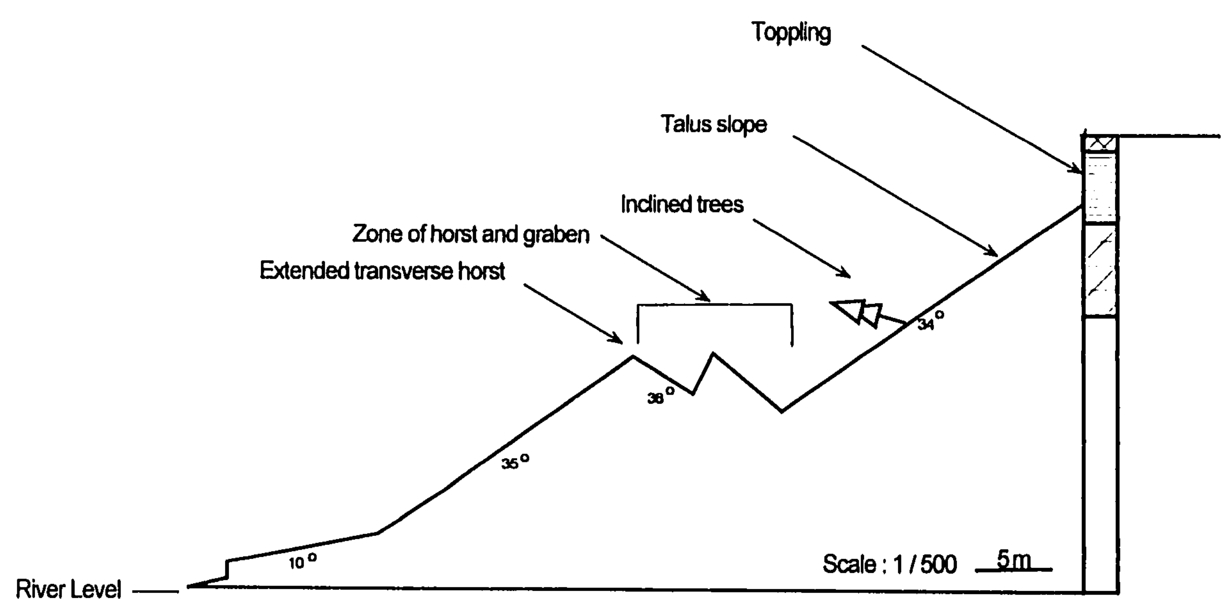
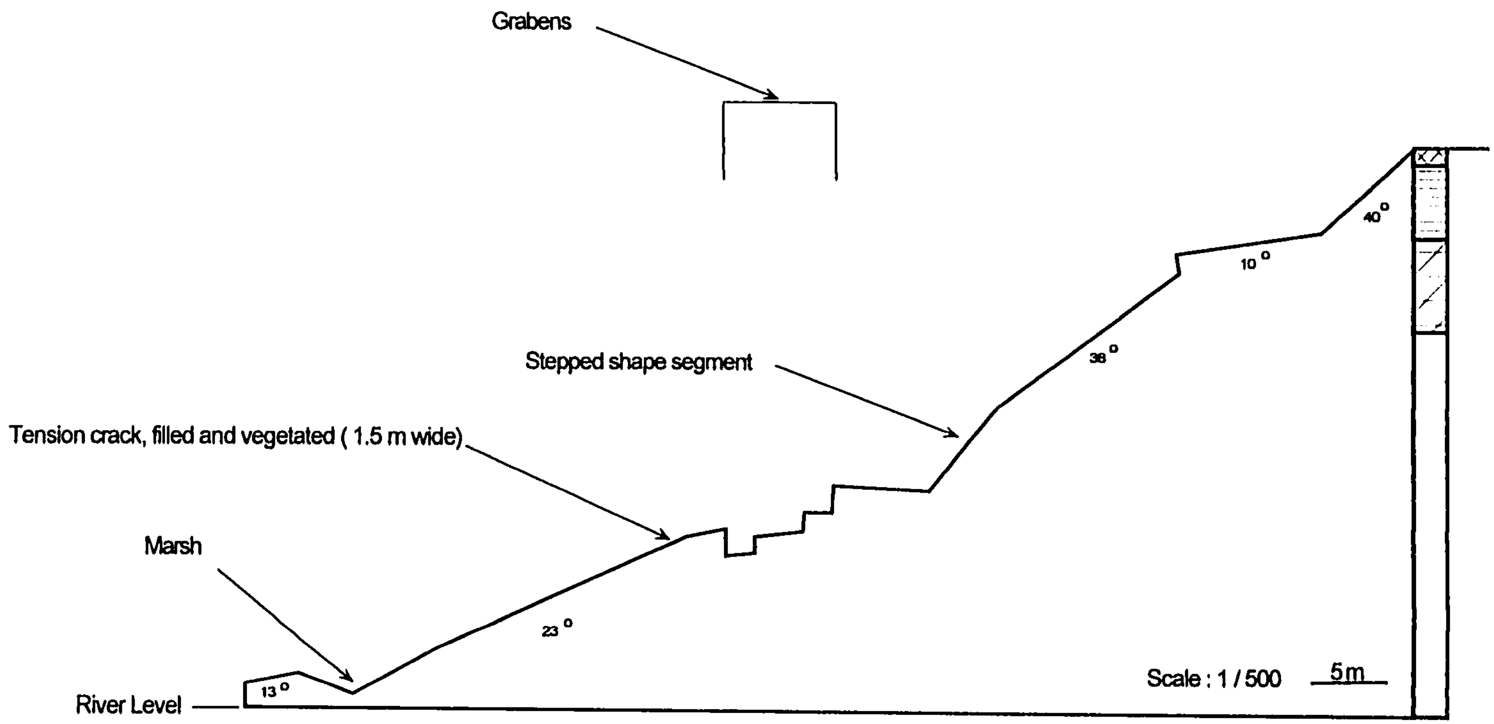


*Fig. 6.10 - Longitudinal Profile, P-13B, at Loc. 13,* **(looking downstream)**



**Loc. 14**

The plan of this location, Fig. 6.11, shows the transverse horst extends almost across the landslide. It is curved but generally is parallel to the main scarp. At both ends, near the flanks, the transverse horst changes to a sharp break in slope. The downstream flank of the landslide coincides with a narrow trench running all the way from the upland to the river level. The upstream part of the landslide toe is concave (upstream of profile P-14B) and the downstream part is convex. The previous talus slope is now vegetated with young trees and talus deposits are not visible anymore. The accumulation zone is vegetated by old dried trees inclined upslope. The landslide toe is covered with shrubs and few young trees.

Two profiles, P-14A and P-14B, have been constructed for this location, Figs.6.12 and 6.13. The upslope part of the profile, P-14A, Fig. 6.12, is common with that of profile P-14B, Fig. 6.13.

At profile P-14B, the slope containing a shallow movement is covered only by grass.

**Loc. 15**

Profile P-15, Fig. 6.15, shows a small vertical scarp, 1.5 m high. The other noticeable feature is the existence of a flat segment at upslope part of the accumulation zone. This flat segment is followed downslope by a segment containing horst and graben. The lower part of the slope that contains the shallow movement is bare.

*Fig. 6. 11 - Plan of loc. 14*

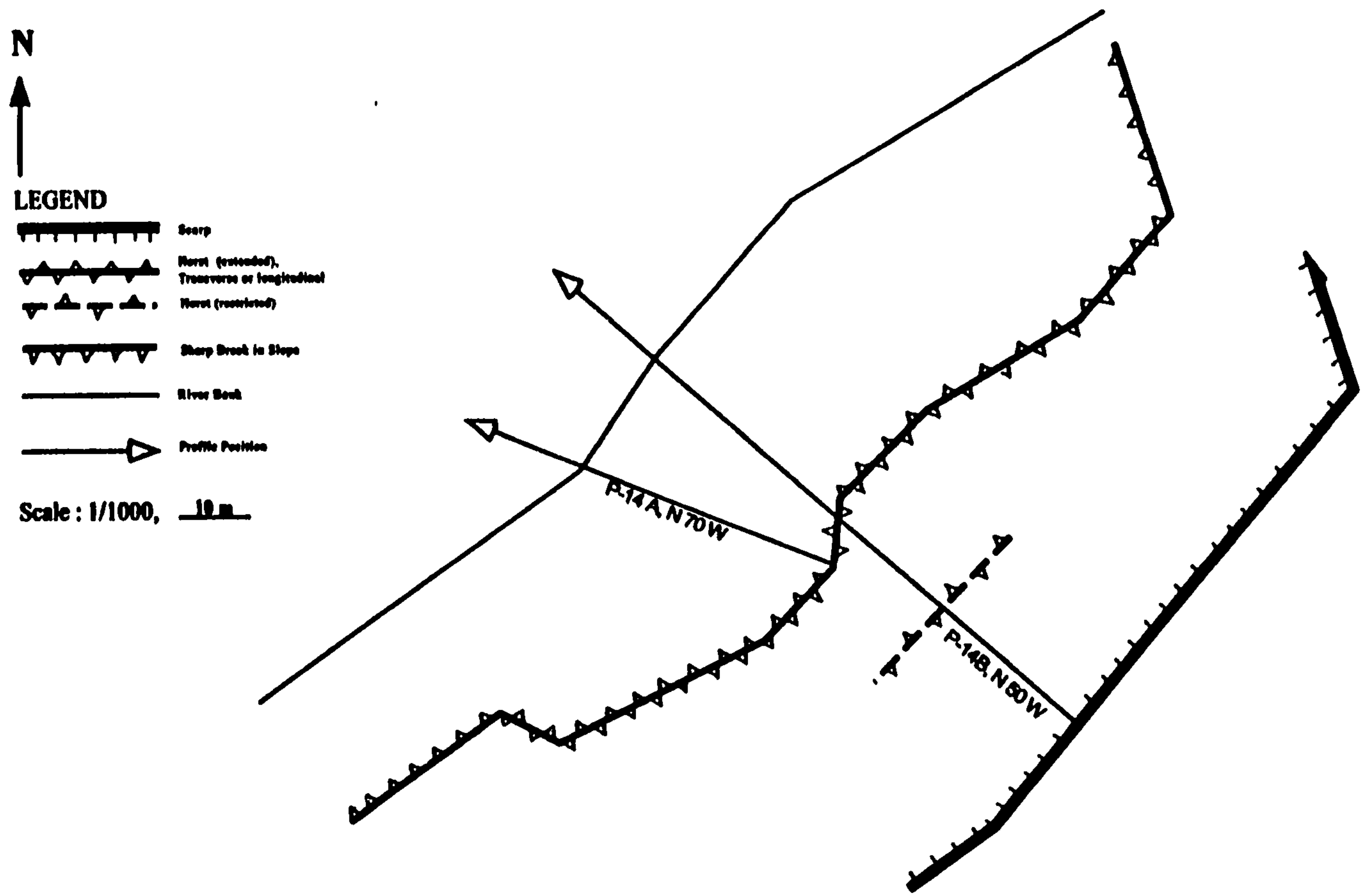


Fig. 6.12 - Longitudinal Profile, P-14 A, at Loc. 14, (looking downstream)

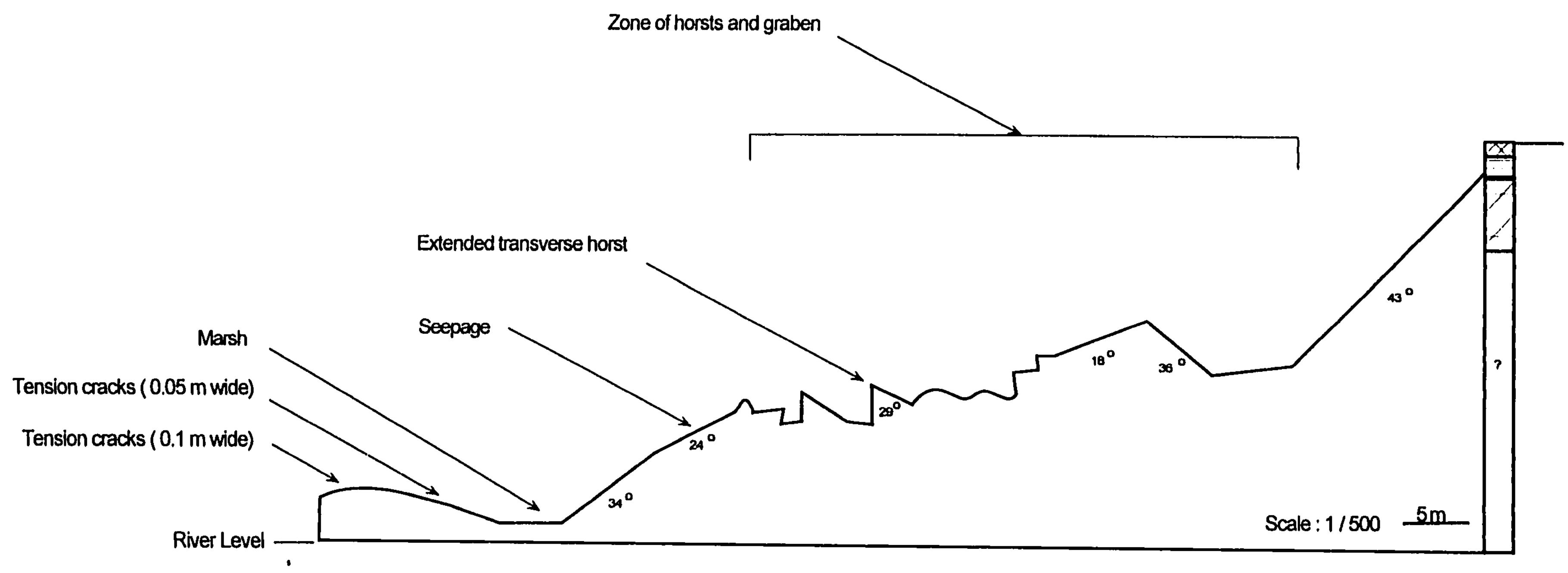


Fig. 6.13 - Longitudinal Profile, P-14B, at Loc. 14, (looking downstream)

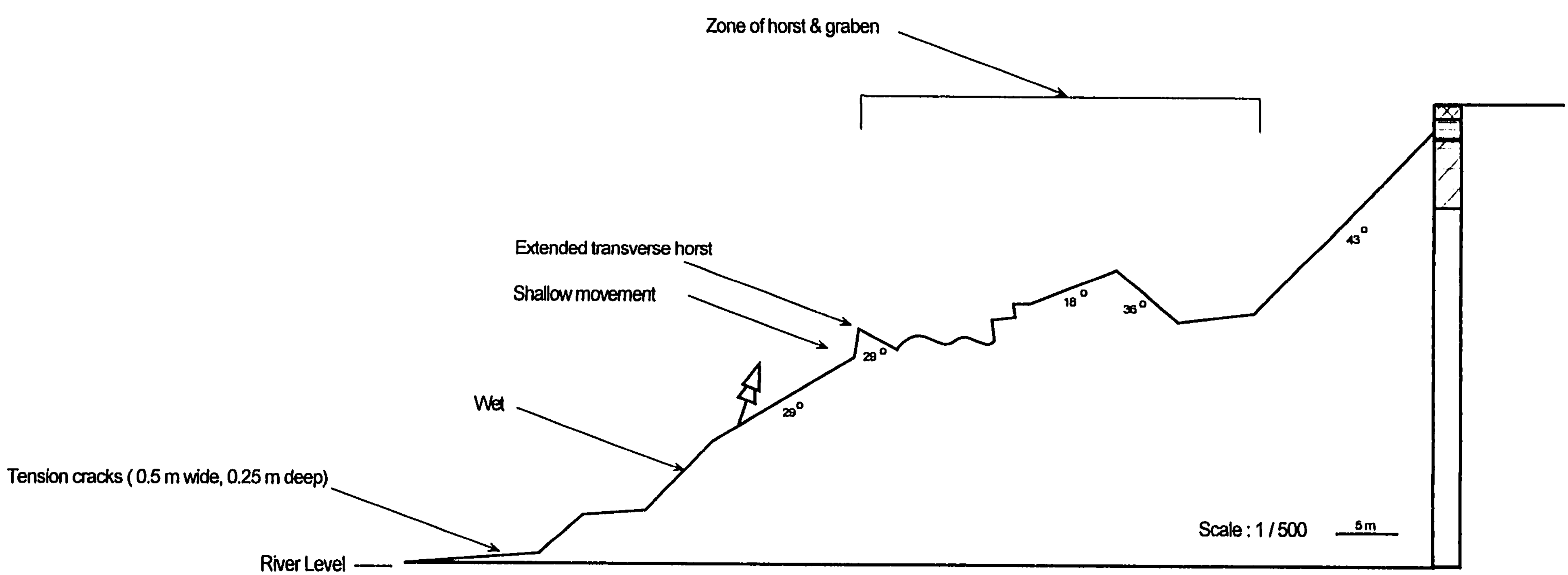


*Fig. 6. 14 - Plan of Loc. 15*

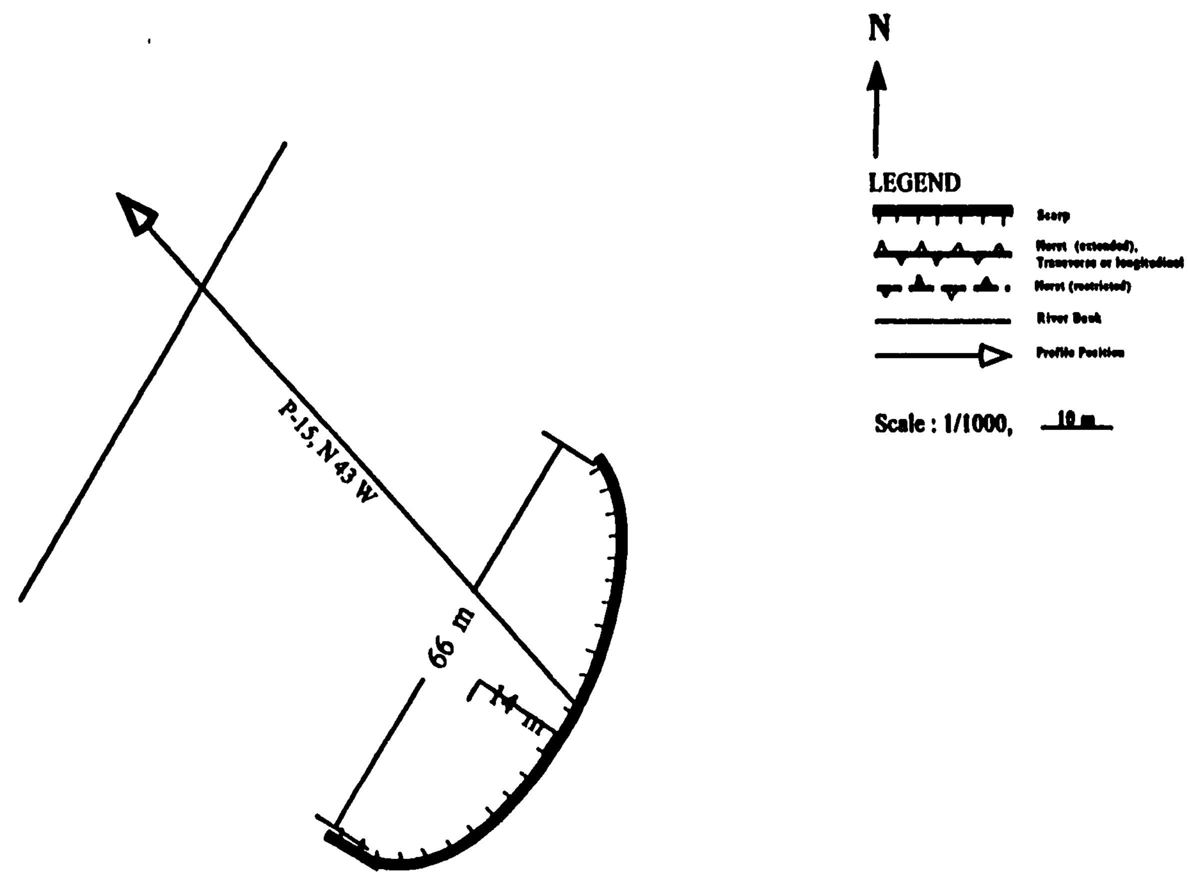
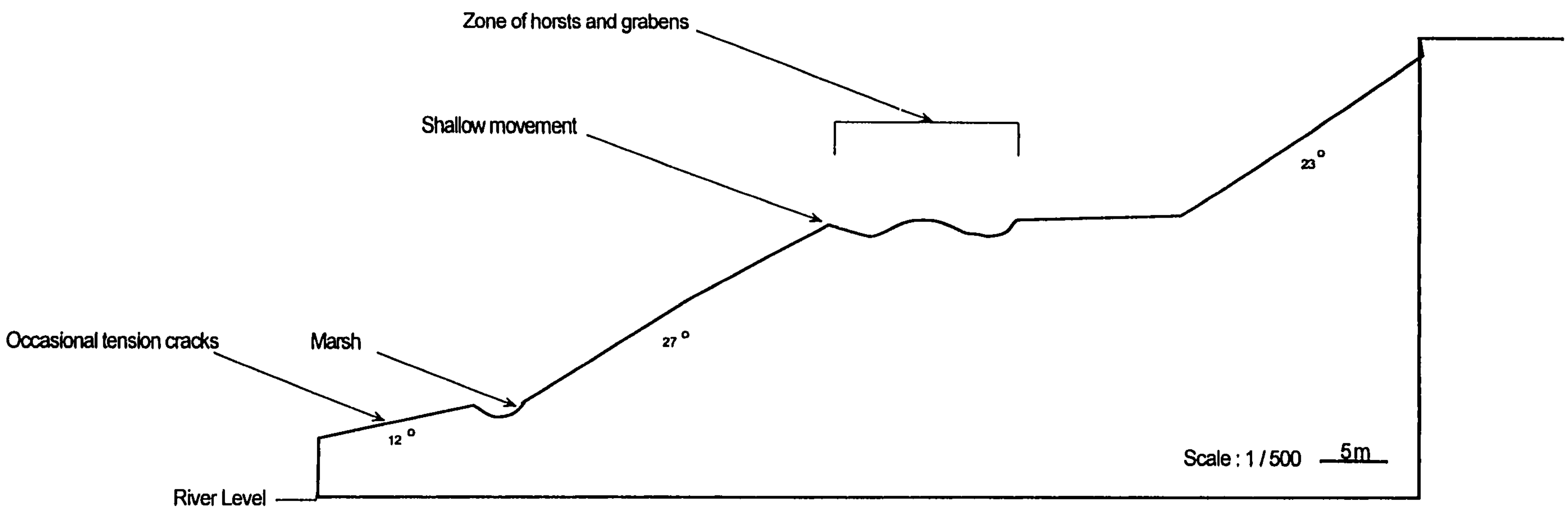


*Fig. 6. 15- Longitudinal Profile, P- 15, at Loc. 15,* **(looking downstream)**



**Loc. 16**

As shown in plan of Loc. 16, Fig. 6.16, a sharp break in slope exists but is not very extensive and is located on the downslope part of the accumulation zone. The vegetation covering this slope consists of old dense dried and upright trees (spruce). The river beach is sand and 5 m wide.

Profile P-16A, Fig. 6.17, shows a very short vertical scarp. The accumulation zone has been greatly depressed and the graben and horst are no longer visible. Only, on the very downslope part of the accumulation zone, one graben (large tension crack) exists. Consequently, a large concave-up part comprises most of the slope.

Profile P-16B, Fig. 6.18, shows the slope is composed of two convex-up parts.

Profile P-16C, Fig. 6.19, seems to represent an undisturbed slope. The flat segment at the middle seems to be a terrace relict 5 m above the North Saskatchewan River level. The vertical segment following that flat segment could be the riser of the terrace.

**Loc. 17**

The upper part of this location is a depression area, which resembles a quarter of a sphere. Moving downslope, the depression narrows and becomes a wide trench. At 2 m above the river level, there is a small spring coming out of the slope. Its water stinks and contains white materials. The vegetation at this location consists of young, sparse and upright trees.

*Fig. 6. 16 - Plans of Loc. 16 and Loc. 17*

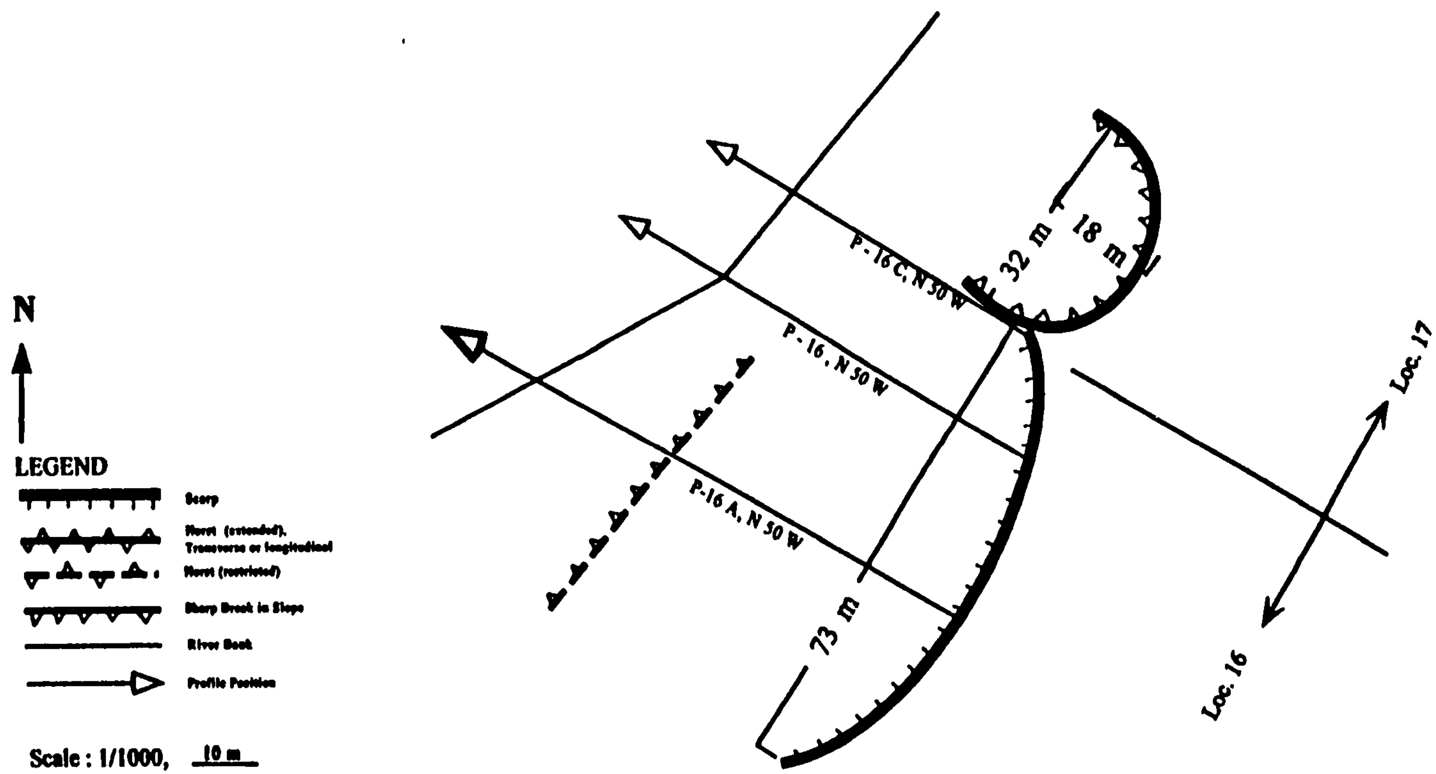


*Fig. 6. 17 - Longitudinal Profile, P-16 A, at Loc. 16,* **(looking downstream)**

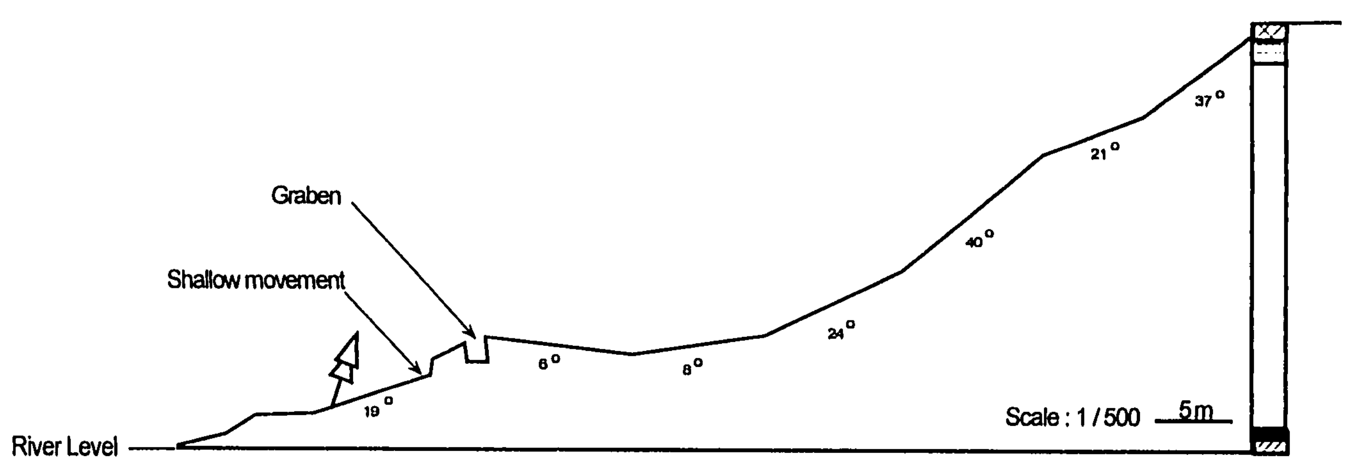


*Fig. 6. 18 - Longitudinal Profile, P- 16 B, at Loc. 16,* **(looking downstream)**

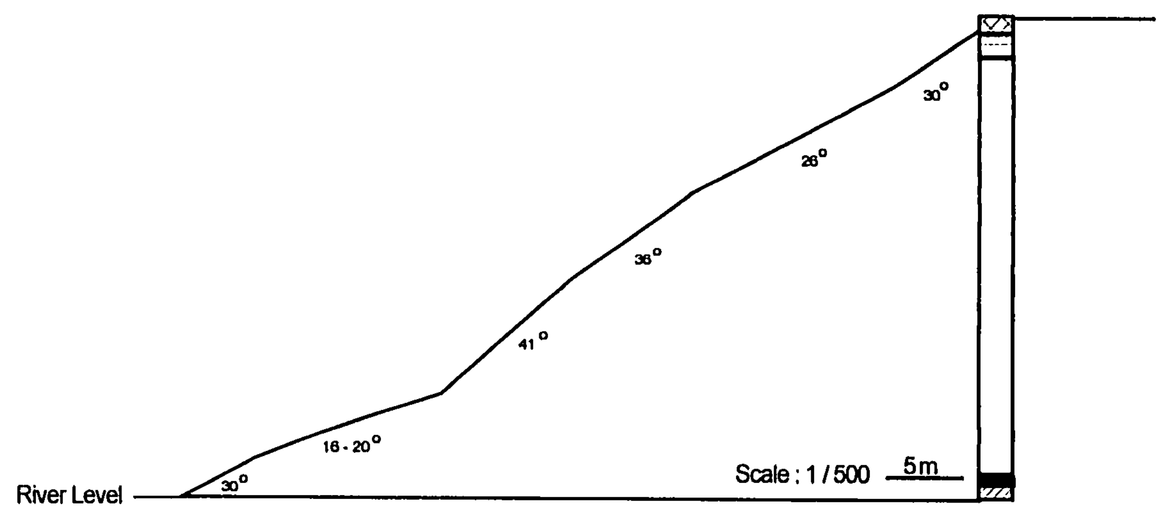
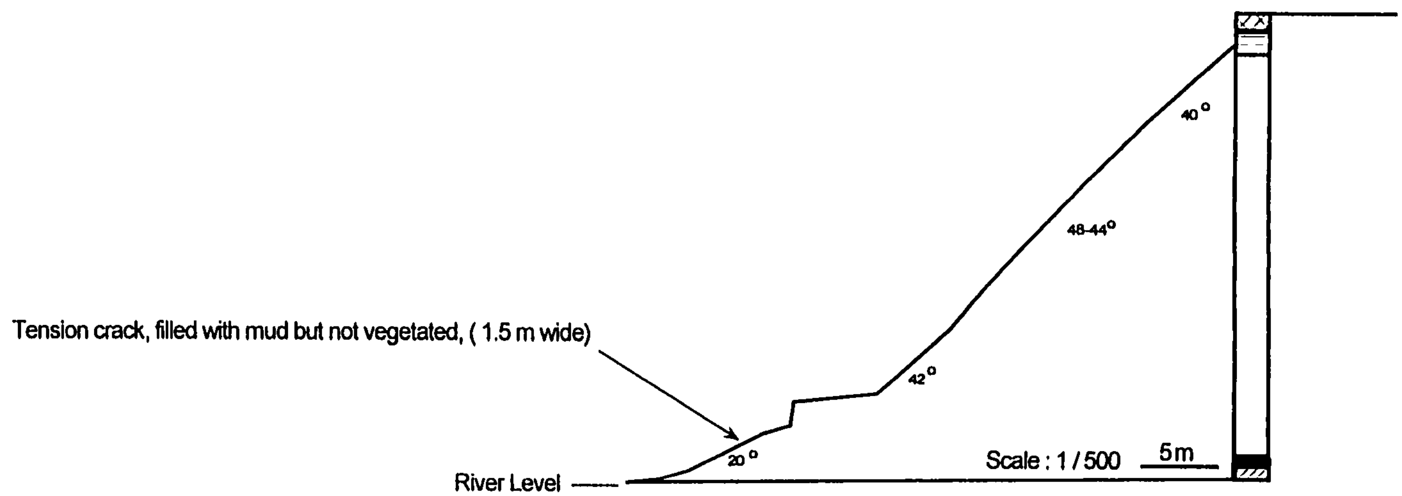


*Fig. 6.19 - Longitudinal Profile, P-16 C, at Loc. 16,* **(looking downstream)**



**Loc. 21**

Fig. 6.21 shows the profile P-21. The slope is highly vegetated (dense) with old trees.

**Loc. 22**

Fig. 6.22 shows the profile P-22. As is visible from the profile, the accumulation zone has been depressed and neither grabens nor horsts is visible anymore. Most of the lower slope is concave-up shape. The peculiar feature is a segment that seems to have been forced upward. That could be a rotated block as a result of a shallow rotational slide, which represents a transverse horst. However, it is not clear how extended it is transversely.

**Loc. 23 and Loc. 24**

The upland (slope crest) elevation at Loc. 23 starts to drop towards the downstream, Subsequently, at downstream part of the Loc. 24, the crest reaches to the river level where it is the intersection of the North Saskatchewan River and the Oldman Creek. No profile was provided for the Loc. 24.

Fig. 6.24 shows the profile P-23. A noticeable feature is that there is neither horst nor graben. The concave-up part of the slope is smaller compared to Loc.10, 15, 16 and 22. Also the base of the concave-up part is at higher elevation. The concave-up part is vegetated with shrubs and a few young trees. Moving downslope from the concave-up part, the slope is vegetated with dense old trees. Some small shallow movements are visible at the toe of slope.

*Fig. 6.20 - Plans of Loc. 21 and Loc. 22*

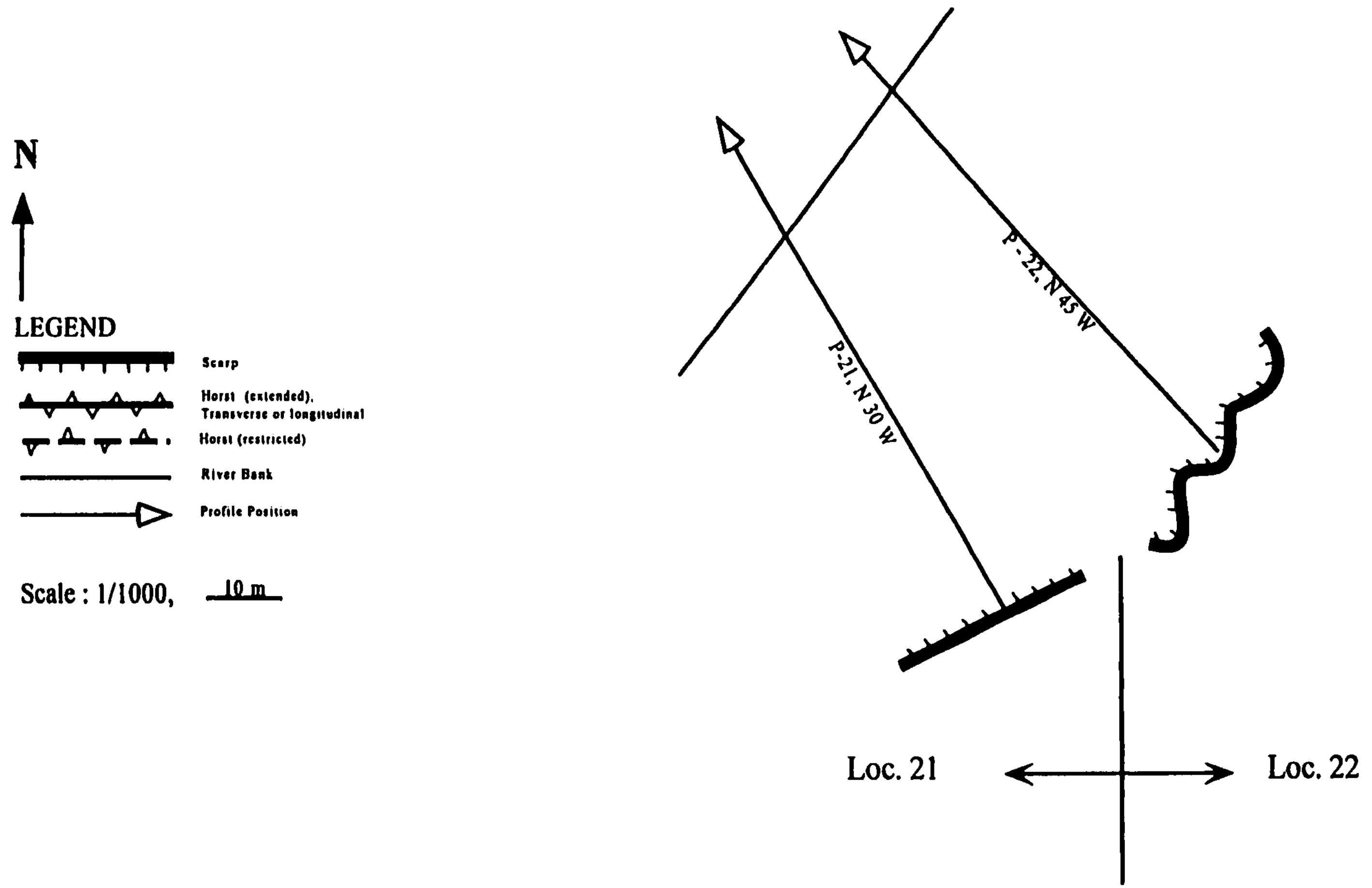


*Fig. 6. 21- Longitudinal Profile, P-21, at Loc. 21,* **(looking downstream)**

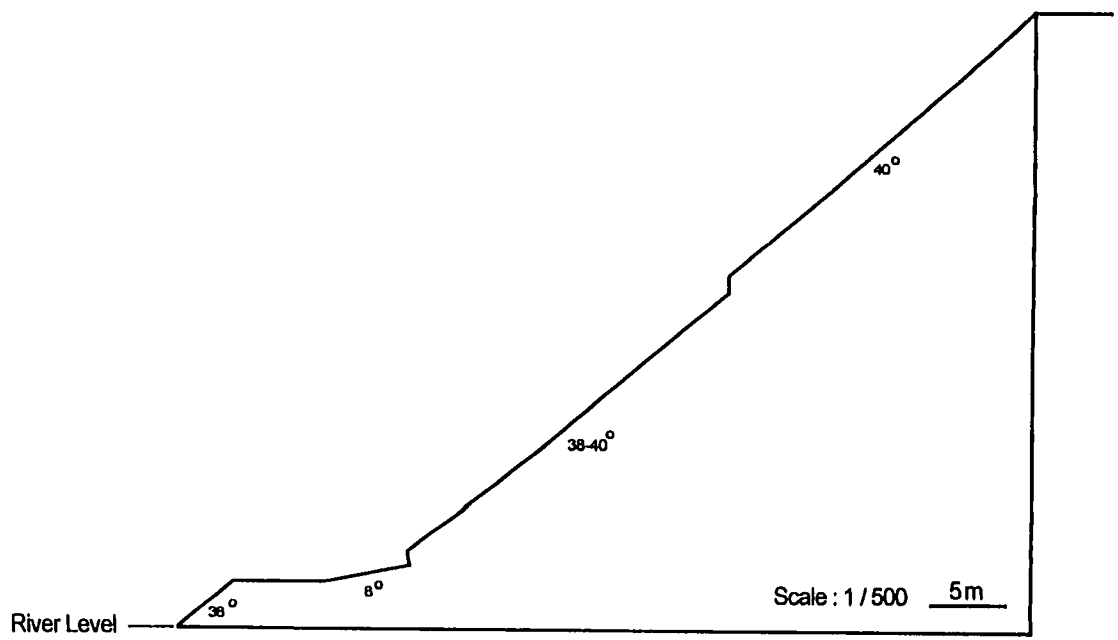


*Fig. 6.22 - Longitudinal Profile, P-22, at Loc. 22,* **(looking downstream)**

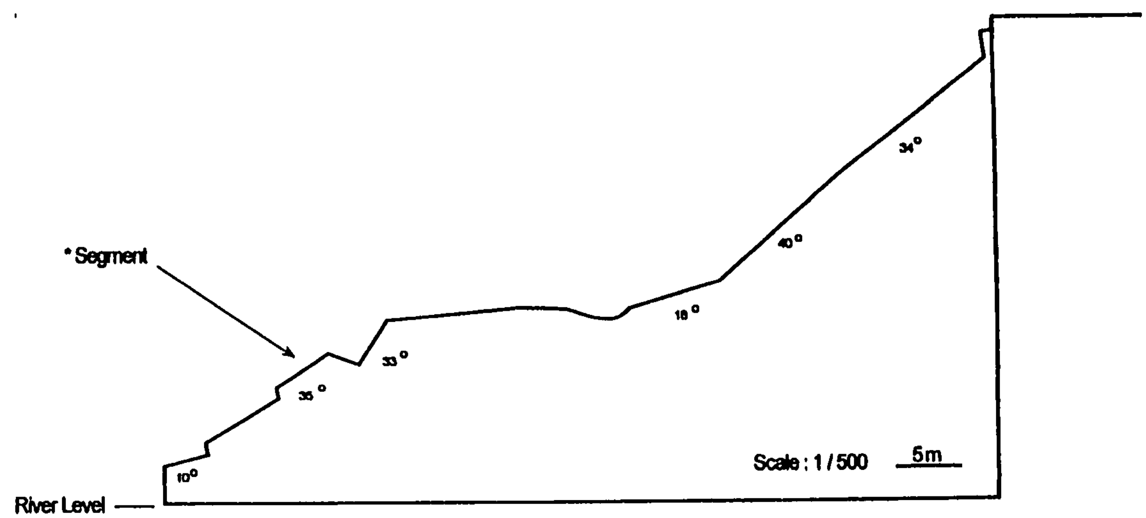


*Fig. 6. 23 - Plans of Loc. 23 and Loc. 24*

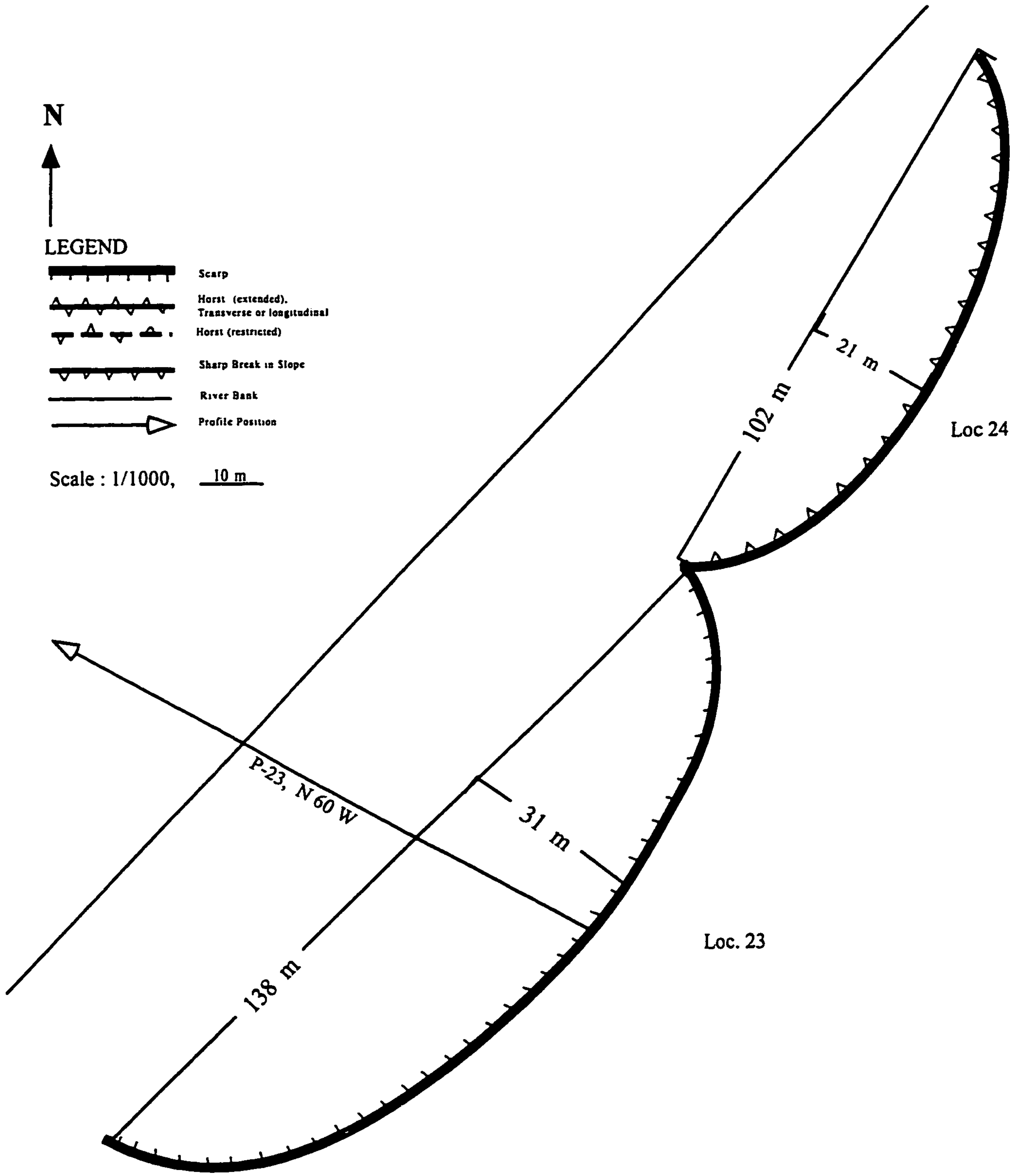
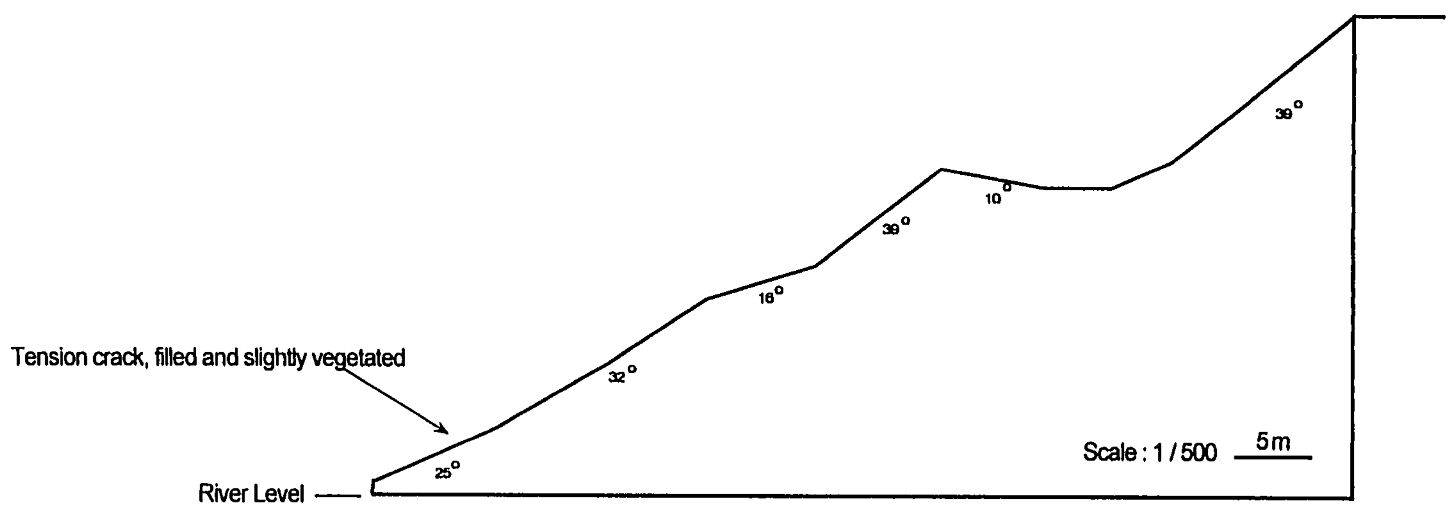


*Fig. 6.24 - Longitudinal Profile, P- 23, at Loc. 23, (looking downstream)*



**Loc. 26**

This location is at the upstream limit of the Oldman landslide succession. It is located about 50 m downstream of the intersection of the North Saskatchewan River and the Oldman Creek.

The profile P-26, Fig. 6.26, shows that the slope consists of two parts. The upslope part which is concave-up and the downslope part which is a steep segment at 45°. The concave-up part is vegetated with old upright trees that are dried up to half of their heights. The horizontal portion of the concave-up part contains tension cracks. The steep part of the slope has experienced shallow movements and is bare.

**Loc. 27**

The plan of this location is represented in Fig. 6.27. The elevation of the scarp is few meters lower than that of the upland. If moving backward from the scarp, a pond will be intersected at the upland area. River beach is sand and convex.

Profile P-27, Fig. 6.28, shows the slope is concvex-up at the upslope part and then it becomes concave-up.

*Fig. 6.25 - Plan of Loc. 26*

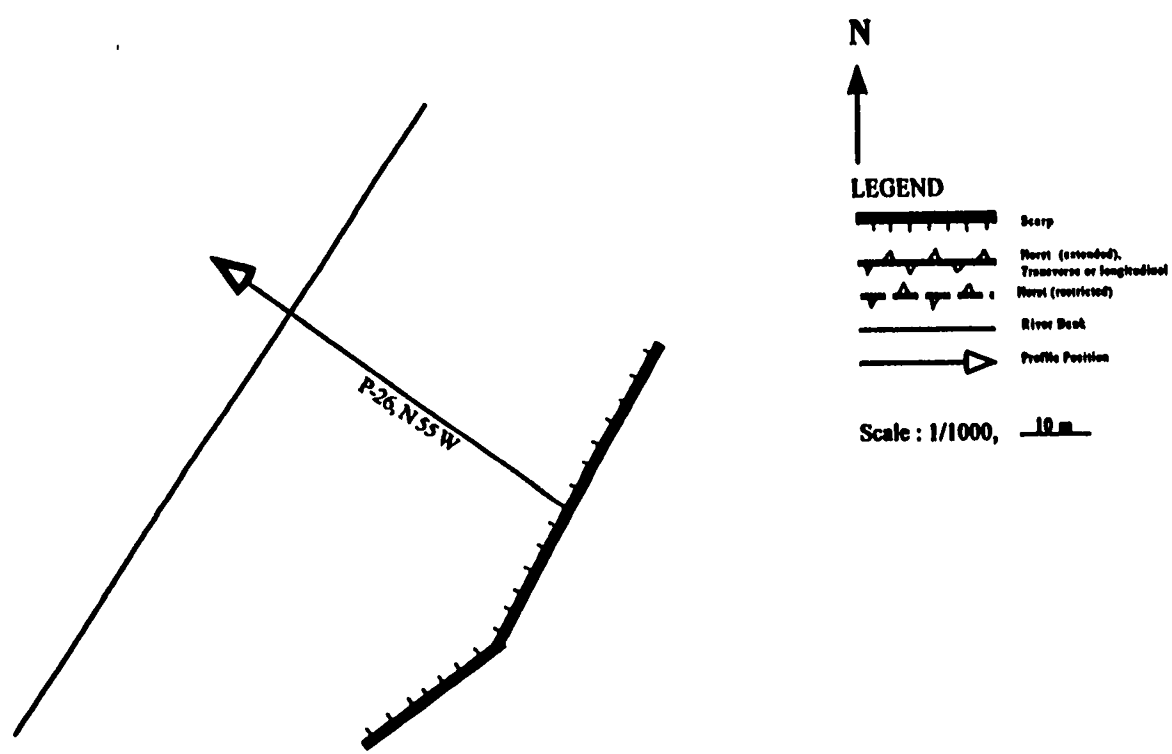
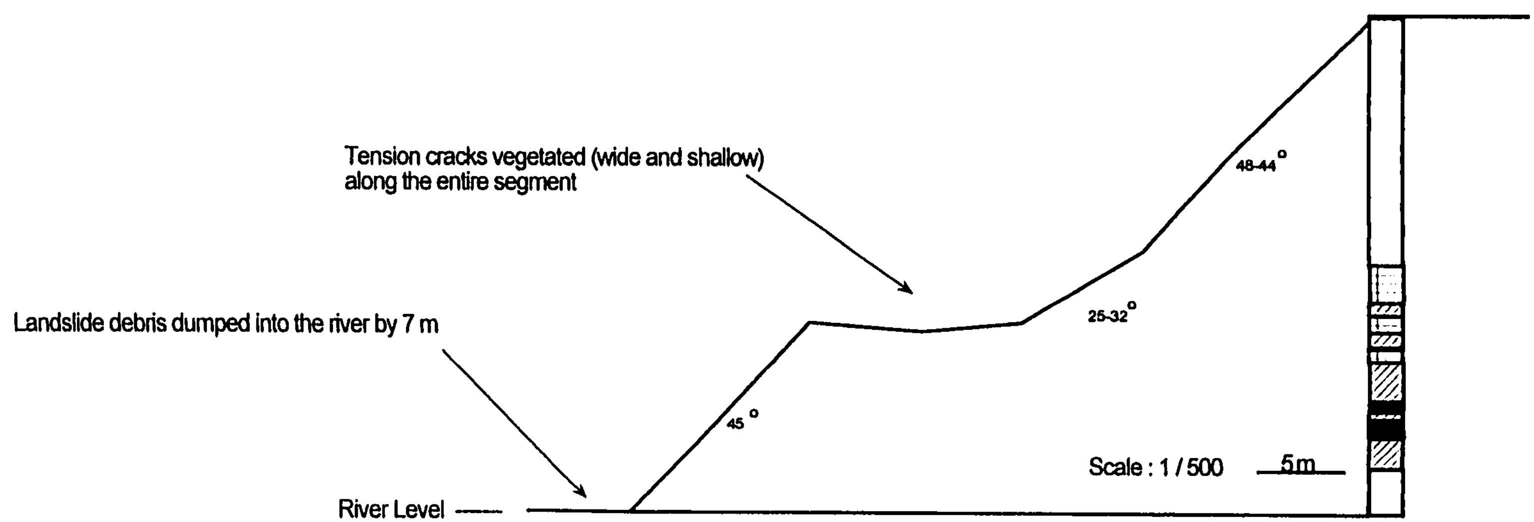


*Fig. 6.26- Longitudinal Profile, P-26, at Loc. 26,* **(looking downstream)**



## *Fig. 6.27 - Plan of Loc. 27*

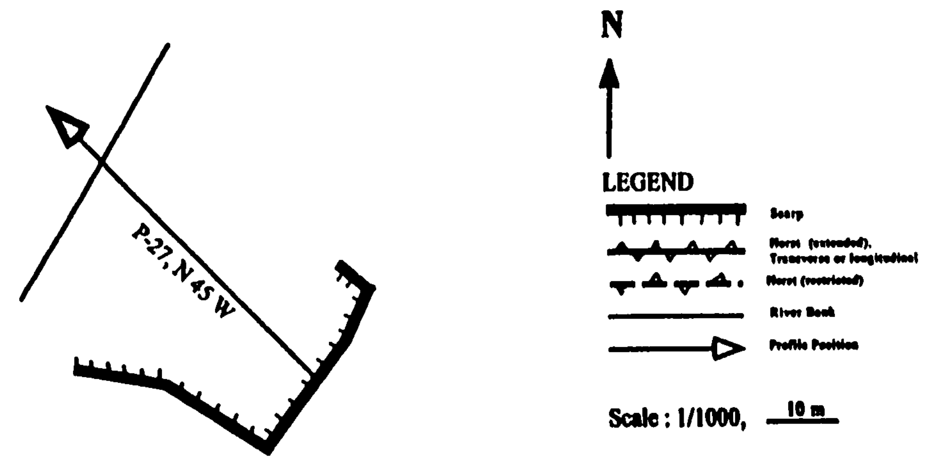
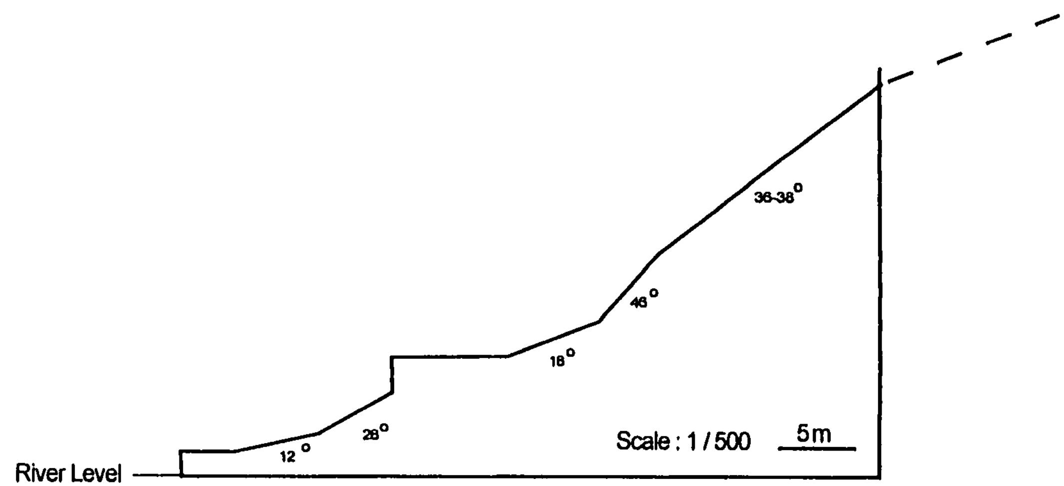


*Fig. 6.28 - Longitudinal Profile, P-27, at Loc. 27,* **(looking downstream)**



**Loc. 30**

The plan of this location is shown in Fig. 6.29. The profile P-30, Fig. 6.30, shows that if moving from the top of the slope to the river level, the upper part is concave-up. This part is vegetated with shrubs and few old upright trees. Downslope of this concave-up part, the slope is convex-up. The upslope part of this convex-up part is vegetated by sparse young trees and shrubs and its downslope part with dense old upright trees that are dried up to the two third of their heights.

**Loc. 31**

Fig. 6.31, Profile P-31, shows the slope consists of two convex- up parts, overall.

**Loc. 32**

As Fig. 6.32 represents the profile P-32, the slope contains a concave-up part at top, which is followed at downslope with a convex-up part.

**Loc. 36**

Profile P-36, Fig. 6.33, shows a vertical scarp of 2 m for the slope. The scarp elevation is almost at two third of the upland elevation. The slope consists of segments standing at the almost same angle, average 37°. The slope is mostly composed of sands and is covered by grass and bushes. The river beach is fine sandy mud.

Fig. 6.29 - Plan of Loc. 30

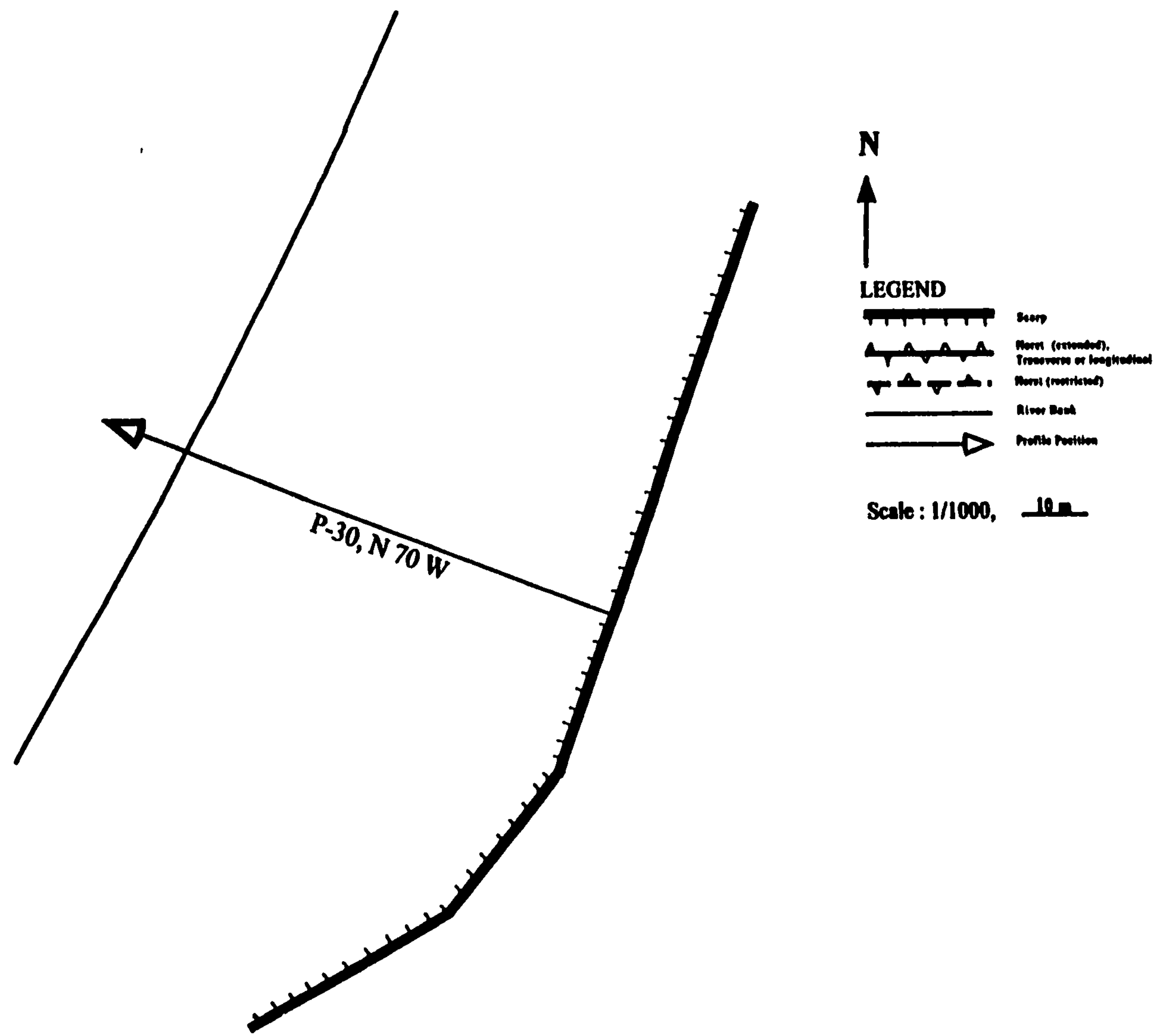
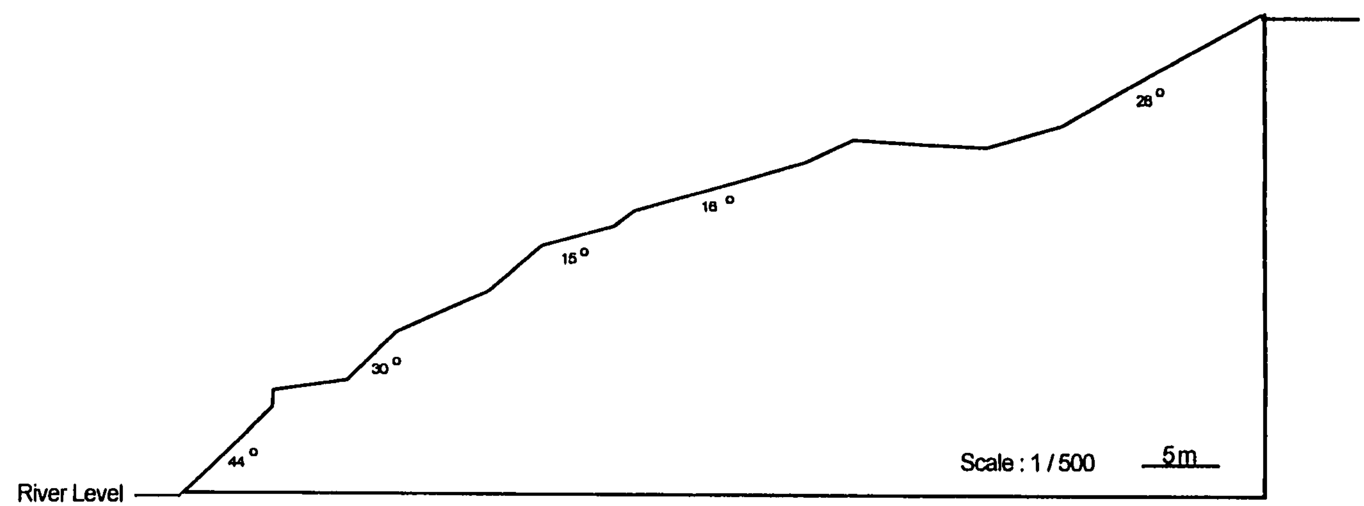


*Fig. 6. 30 - Longitudinal Profile, P-30, at Loc. 30,* **(looking downstream)**



## *Fig. 6. 31 - Longitudinal Profile, P-31, at Loc. 31,* (looking downstream)

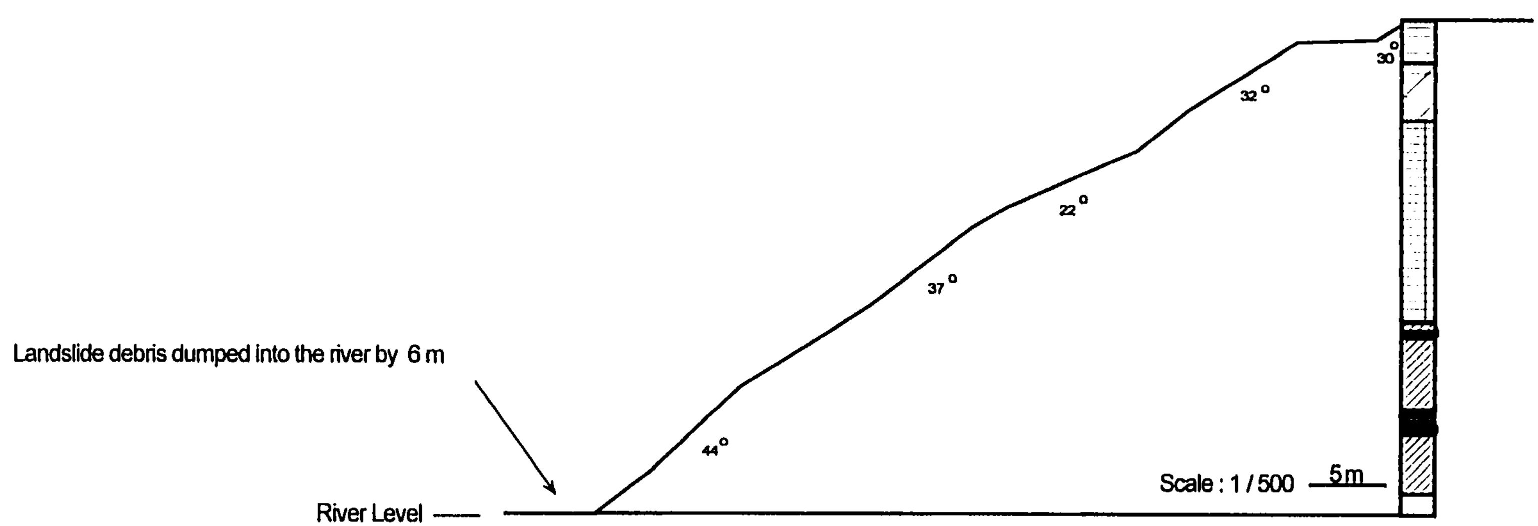
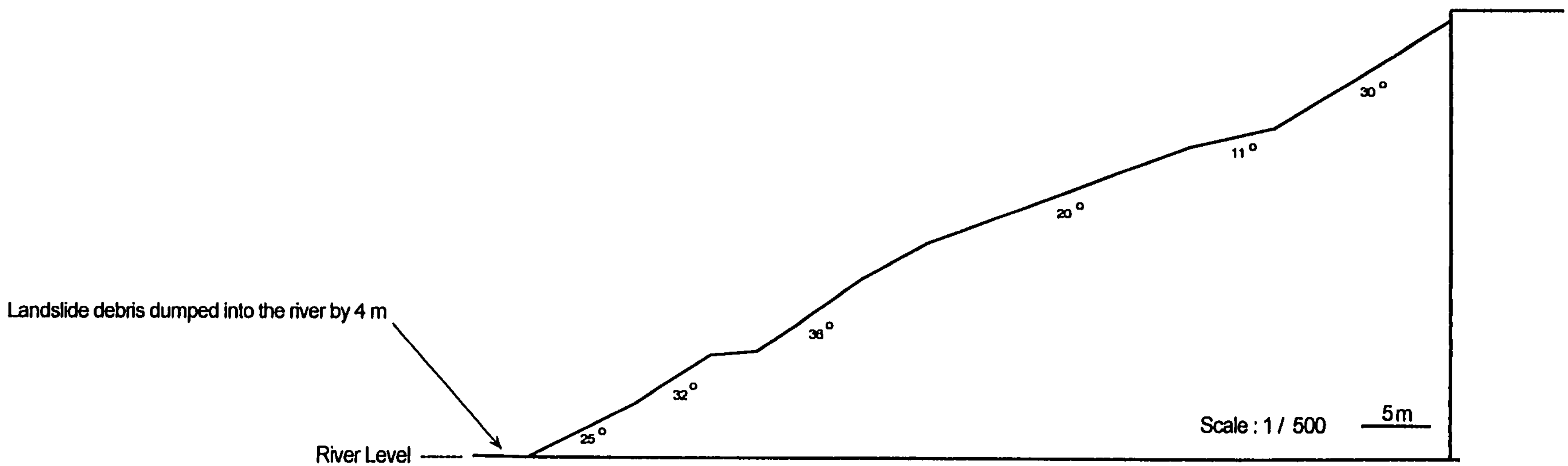
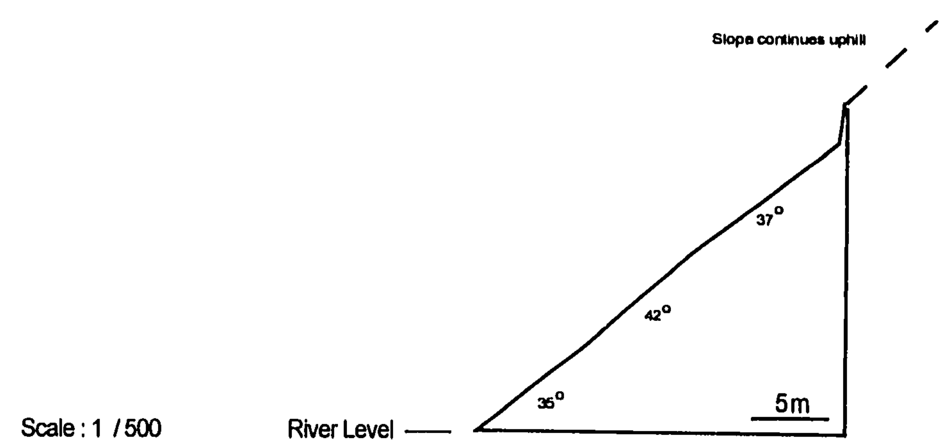


*Fig. 6. 32 - Longitudinal Profile, P-32, at Loc. 32,* **(looking downstream)**



## *Fig. 6. 33 - Longitudinal Profile, P- 36, at Loc. 36,* (looking downstream)



**Loc. 37**

This location is very similar to location 36 from points of the scarp elevation, the slope concavity or convexity, sand material comprising the slope and the vegetation. But it has no vertical scarp and the river beach is mud with gravel (Fig.6.34).

**Loc. 38**

The slope mostly consists of sands. The toe is convex and the river beach is mud with gravel (Fig. 6.35).

Profile P-38, Fig. 6.36, indicate that the slope contains a 5 m vertical scarp which is bare. Downslope of the main scarp, the slope is concave-up. On the lower portion of the concave-up part, the displaced old trees have been accumulated and they are inclined upslope. Downslope of the concave-up part, the slope is steep and very undulating.

*Fig. 6. 34 - Longitudinal Profile, P- 37, at Loc. 37,* **(looking downstream)**

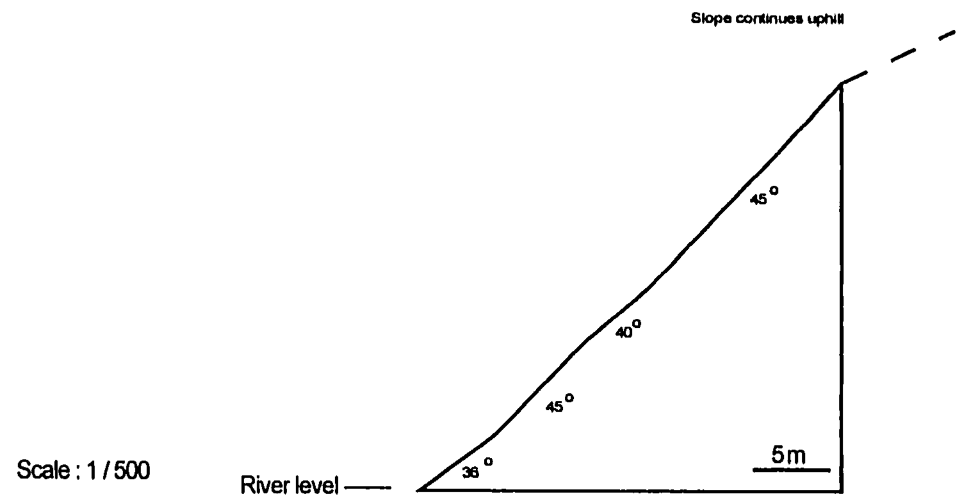


*Fig. 6.35 - Plan of Loc. 38*

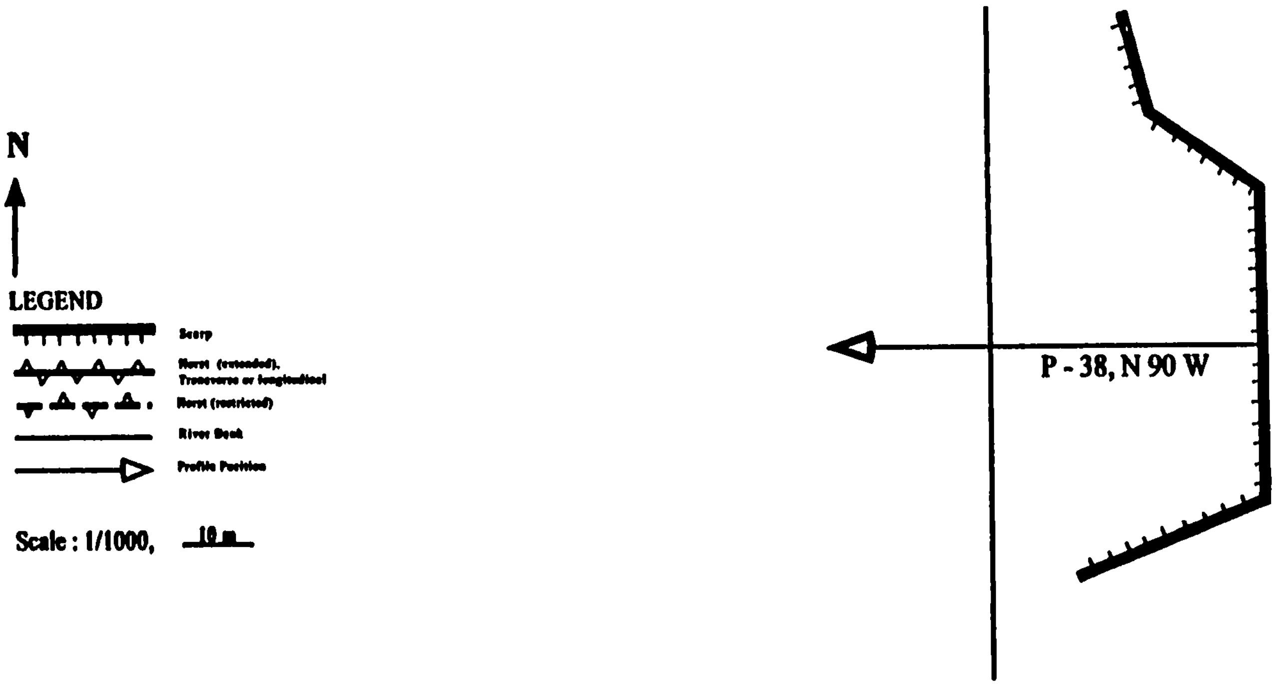
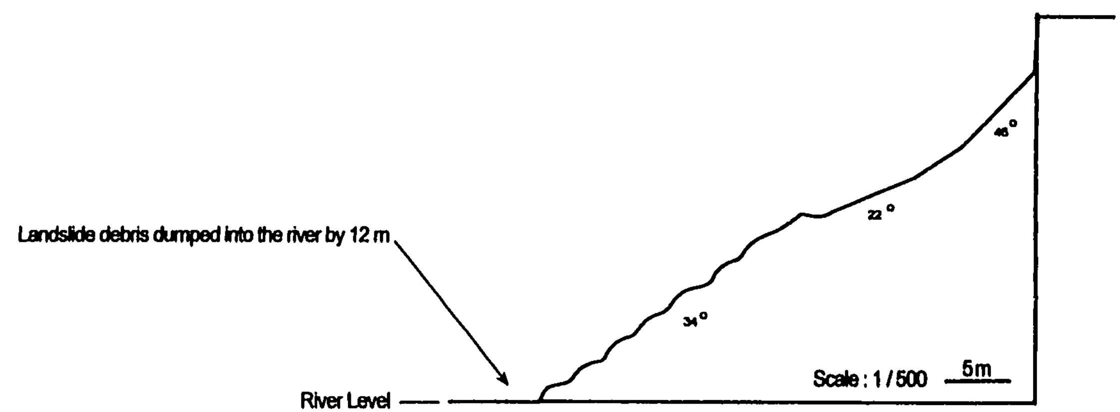


*Fig. 6. 36 - Longitudinal Profile, P-38, at Loc. 38,* **(looking downstream)**



**- Overall Slope Angles along the Lesueur Landslide Succession**

The following is the summary of the overall slope angles and the total lengths along the Lesueur and Oldman landslide successions. It should be noted that the total length measured here is slightly different from the definition introduced in Cruden and Varnes (1996). It is the distance between the crest and the toe of slopes instead of the tip of the slides.

Table 6.1 - Summary of the overall slope angles and total lengths for the profiles provided

| Profile No. | Overall Slope Angle (°) | Total length (m) |
|---|---|---|
| P-9A | 18 | 100 |
| P-9B | 20 | 96 |
| P-9C | 18 | 73 |
| P-10 | 22 | 82 |
| P-11 | 24 | 75 |
| P-13A | 21 | 67 |
| P-13B | 26 | 86 |
| P-14A | 19 | 95 |
| P-14B | 23 | 93 |
| P-15 | 22 | 91 |
| P-16A | 21 | 77 |
| P-16B | 30 | 62 |
| P-16C | 36 | 50 |
| P-21 | 35 | 70 |
| P-22 | 28 | 75 |
| P-23 | 26 | 73 |
| P-26 | 33 | 65 |
| P-27 | 29 | 54 |
| P- 30 | 22 | 78 |
| P-31 | 31 | 68 |
| P-32 | 25 | 76 |
| P-36 | 40 | 33 |
| P-37 | 43 | 36 |
| P-38 | 37 | 59 |

## 6.3 - DISCUSSION AND CONCLUSIONS

The discussion and conclusions are divided into two sections. One is based on the comparison between the results of the control surveying and the ground surveys and the other is based only on the ground surveys results.

**-Comparison Between the Results of the control surveying and the Ground Surveys**

The longitudinal horsts extend in a NW direction. The left scarp of the landslide also extends in NW direction, considerably, and continues almost to the river level. The trend of the displacement vectors of the G series of standpipes was found by the slope movement monitoring to be in NE direction.

Having longitudinal horsts and tentional cracks that extended parallel to the left scarp of Lesueur landslide and displacement vectors of the G series of standpipes perpendicular to the direction of the left scarp suggest that they could be produced by a displacement initiated from the left scarp.

The displacement vectors of hubs are almost perpendicular to the direction of the central part of the main scarp.

As there is no overlap time between the measurements of standpipe and hub displacements, one question remains to be answered, which is as follows. Is the displacement of mass periodic and occurs at intervals? Is it influenced by the left scarp for a period of time (e.g. 1964 - 1995) and during another period is governed by the central part of the main scarp (e.g. 1996- 1997)

### -Ground Surveys Results

As one of the crucial elements in determining the mode of a slide is the shape of its surface of rupture, the following discussion tries to define the geometry of the surface of rupture and determine its shape from the slopes' geometry along the landslide successions. However, the results of this research can not locate the exact position of the surfaces of rupture because of the lack of the subsurface data.

The geometry of the displaced mass of most of the landslides along the Lesueur succession are similar to each other as the Oldman ones are also similar to each other. As the same external geometries show the same deformation pattern for the displaced mass, therefore, it indicates a common mechanism for the landslides.

The landslides are divided into two groups. The discussion of the type of movement and mode of sliding is also classified into the same groups as follows: upstream and downstream which are called Lesueur and Oldman groups, respectively.

### Lesueur Group

The landslides classified in this group are at locations 9, 10, 11, 13, 14, 15, 16 and 22. Although the landslide at Loc. 23 is located in the Lesueur succession, it is not classified in this group as it represents different behavior. All landslides in this group have the following characteristics for their longitudinal profiles: one characteristic is that they have a zone of horsts and grabens or at least a graben. Another property is at the downslope part of the accumulation zone, there is a sharp break in slope that usually has experienced a shallow movement.

The Lesueur group of landslide can be classified into two groups: 1) reactivated (and younger), 2) inactive (and older). Landslides at locations 9, 11, 13, 14 have profiles with a pronounced zone of horsts and grabens. At locations 10, 15, 16 and 22, the zone of horsts and grabens has been depressed and they are less visible.

Given the structural elements, such as horsts and grabens, for the Lesueur group of landslides, it is proven that the landslides along that section of its length has a translational surface of rupture. Therefore, the mode of sliding for this group of landslide is compound. The terminology has been adapted from Cruden and Varnes (1996) p.59.

The shallow movements happen in the downslope part of the accumulation zone. This part of the displaced mass is randomly cracked because of the accommodation of the internal deformation when a mass deforms. Therefore, the cracked material can behave as fill, and it is possible to have a rotational surface of rupture. There is also field evidence that supports this idea and that is having trees inclined uphill where the shallow movements occur , Figs. 6.3, 6.4, 6.5 and 613.

As this surface of rupture is small, and is located within the mass of the actual landslide, it can be called an internal rotational surface of rupture. This rotational surface of rupture is suggested as being retrogressive because there is no uphill-facing (back-tilted) segment along these shallow movements. Thus, the process should have started at lower elevation as a small shallow movement and then have retrogressed. It is suggested that the shallow movements in the feet of Lesueur landslides group have internal retrogressive rotational surfaces of rupture. The elevations of these rupture surfaces are not clear but their upper and lower limits can just be estimated. The lowest point of the steep segment at the downslope part of the accumulation zone is at an elevation ranges from 3 to 7 m above river level (607 m a.s.l.). That can be taken as the upper limit of the surface of rupture. The lower limit can be the river level as the riverbed has not shown any disturbances. Therefore, the elevation of the surface of rupture can be bracketed between the river level and ~7 m above that.

Comparison between two groups of reactivated (and young) and inactive (and old) landslides explains the aging process and deformation trend of the slopes. The profiles of the aged landslides (dormant stage), typically P-10 (Fig. 6.5) and P-16A (Fig. 6.17) have a concave-up part, then a steep segment, and finally the toe, moving from the crown to the toe of the landslide. This situation can be explained by the following mechanism. Through time, the accumulation zone of the landslide slowly moves towards the river, therefore, its overall elevation decreases. Meanwhile, the relative elevation difference between the graben and horst decreases as the horst blocks subside. The large concave-up part of the profile through the inactive landslide results from submergence of the depletion zone under the talus from the retrogressing scarp.

The following deformation trend for the displaced mass of a translational landslide can be deduced from the comparison among the long profiles along the upstream group of landslides. Through the aging process, the displaced mass deforms in a way that the slope geometry changes from the typical one e.g. P-11 (Fig. 6.7) or P-14B (Fig. 6.12) to the typical one such as P-10 (Fig.6.5) or P-16A (Fig. 6.17).

**Oldman Group**

The downstream segment of Oldman succession includes landslides whose geometrical properties are different from those upstream. It should be noted that Loc.23 from the Lesueur succession has the same geometrical properties as the landslides in the Oldman succession.

The profiles of the Oldman group of landslides do not show horsts or even grabens (or any other signs of partial translational displacement) e.g. P-23, P-26, P-27, P-36, P-37 and P-38. The segments constructing the geometry of each slope stands more or less at similar angles, and the overall slope angles are steep compared to those of the Lesueur succession. The segments undulate themselves at a scale that can be observed in field, but cannot be shown on graphs. Also, the sizes of the landslides are smaller than those in the Lesueur succession.

Based on the preceding evidence, and the following reasoning, the type of the surface of rupture for the Oldman succession landslides is suggested to be a retrogressive rotational surface of rupture. Consequently, the mode of sliding is rotational.

There is no uphill-facing (back-tilted) segment down the main vertical scarp which typically should exist in a rotational type of failure. There should be a retrogressive, rotational surface of rupture where the shallow movement started from the lower part of the slope. Naturally, the relatively small displaced mass has easily moved downward, being delivered to the river. Then, this change in mass geometry has triggered the further movements in a backward direction. According to Cruden and Varnes (1996), this style of activity is called multiple. This explained mechanism justifies having no uphill-facing segment. However, the surface of rupture is rotational. Also, the aerial photo interpretation indicates the same direction for the enlargement of the bare area on the slopes of the downstream segment through time.

Subsequently, a retrogressive multiple rotational surface of rupture is suggested for the landslides along Oldman succession.

Overall, based on similarities on geometric properties of the landslides, all of the landslides along entire landslide succession are classified into three groups; younger translational landslides (in the Lesueur succession), older translational landslides (in the Lesueur succession) and retrogressive rotational group in the Oldman succession (except one location, Loc. 23, which is in the Lesueur succession)

The following are considered to be the reasons for having different groups of landslides in Lesueur and Oldman successions. As mentioned before, they are postulated as having different surfaces of rupture and modes of sliding.

1) The bedrock surface at Lesueur segment has experienced ice thrusting as the configuration of the bedrock surface in this area shows (Sec 4.4)

2) The bentonite seam at the Lesueur succession has been softened more compared to Oldman succession as the thickness of the bedrock clay shale, which overlies that, is less (Sec. 4.4).

Another reason could be the difference in material comprising the slope between the downstream and upstream segments. As mentioned in the stratigraphic investigation section, the thickness of sands and gravel increases towards the downstream and the material above the bedrock contains more sands and gravel rather than till which is considerably denser and less drained. The above reasoning is not very reliable as there are not enough data points to draw the contact line between the Empress Formation sands and gravel and the till unit (in order to specify the thickness of Empress Formation sands and gravel).

Therefore, ice thrusting at Leuseur succession, and its subsequent softening of bedrock and its bentonite seam, has produced the translational group of landslides whereas in Oldman succession the absence of ice thrusting effects has contributed to the development of a rotational group of landslides.

Based on knowing the types of surface of rupture (mode of sliding), activity status and type of movement, Table 6.2 is provided to specify those characteristics for each landslide.

Table 6.2 Landslide characteristics along the Lesueur and Oldman landslide successions

| ***Location*** | ***Activity*** | | | ***First movement*** | | ***Second movement*** | | ***Mode of sliding*** | ***Remarks*** |
|---|---|---|---|---|---|---|---|---|---|
| | ***State*** | ***Distribution*** | ***Style*** | ***Material Type*** | ***Movement Type*** | ***Material Type*** | ***Movement Type*** | | |
| **9** | Reactivated | Retrogressive | Composite | Rock | Slide | Debris? | Flow? | Compound | Block slide |
| **10** | Inactive | N/A | N/A | Rock | Slide | N/A | N/A | Compound | Block slide |
| **11** | Reactivated | Retrogressive | Complex | Rock | Slide | Debris | Topple | Compound | Block slide |
| **13** | Reactivated | Retrogressive | Complex | Rock | Slide | Debris | Topple | Compound | Block slide |
| **14** | Reactivated | Retrogressive | Single | Rock | Slide | N/A | N/A | Compound | Block slide |
| **15** | Inactive | N/A | N/A | Rock | Slide | N/A | N/A | Compound | Block slide |
| **16** | Inactive | N/A | N/A | Rock | Slide | N/A | N/A | Compound | Block slide |
| **22** | Inactive | N/A | N/A | Rock | Slide | N/A | N/A | Compound | Block slide |
| **23** | Inactive | Retrogressive | N/A | Rock | Slide | N/A | N/A | Rotational | |
| **26** | Inactive | Retrogressive | N/A | Rock | Slide | N/A | N/A | Rotational | |
| **27** | Reactivated | Retrogressive | Multiple | Debris | Slide | N/A | N/A | Rotational | |
| **38** | Reactivated | Retrogressive | Multiple | Debris | Slide | N/A | N/A | Rotational | |

# Chapter 7 CONCLUSIONS

The conclusions are categorized as follows: triggering factors, reactivation period, rate and type of movements of the Lesueur landslide (Loc. 9), slope deformation pattern and the last category is the types of the surface of rupture and the mode of movements.

## Triggering Factors

The triggering factors for the slope movements determined by this research are:

1) The landuse changes, dumped wastes of mining on the north side of the riverbed and tree clearance at the upland area of the Lesueur landslide (between 1952-1962) are considered to be triggering factors for landslide initiation (Sec. 5.3.3).

2) At Loc. 27 and Loc. 38, the landuse change, development of the industrial units on the upland area, are considered to be a second degree triggering factor for the landslide reactivation but not for their initiation (Sec. 5.3.3).

3) The occurrence of a landslide can trigger the initiation of another landslide at its downstream location, by modification of the river flow pattern (Sec. 5.3.3).

## Reactivation Period

1) The flow pattern of the North Saskatchewan River has periodic movement having periods of river erosion and recession as the river shifts to the side banks periodically (Sec. 5.2.3).

2) From 1986 to 1992, the south bank experienced river recession and, since 1992, the period of river erosion has returned (Sec5.2.3),

3) The main mechanism behind the river erosion and recession is suggested to be the channel migration rather than the water level fluctuations (Sec. 5.2.3),

4) As the period of landslide reactivation is coincident with the return of the period of river erosion, the reason behind the reactivation of 6 landslides along the landslide succession, (Table 5.6) during the past few years, is proposed to be the return of the period of river erosion (Sec. 5.3.3).

**Slope Deformation Pattern**

1) Through the aging process of a landslide, the change of the slope geometry (deformation pattern) is from typical profiles such as P-11 or P-14B to P-10 or P-16A. Consequently, the inactive disturbed slope has a large concave-up part comprising most of the slope (Sec.6.3).

2) Producing the longitudinal horsts at Lesueur landslide and displacement of G series of standpipes seems to be governed by the left scarp of the Lesueur landslide.

**Rate and Type of Movement of the Lesueur Landslide (Loc. 9)**

1) The results of the control surveying and the erosion survey show the following: the displacement of the displaced mass at the landslide toe was found to be 0.87 m per year as an average of 3 hubs at the toe. The toe of the Lesueur landslide has receded - 1.83 m from 1996 to 1997. The river erosion (1996-1997) at this part of the toe has been 2.7 m as an average (Sec. 5.1.3). It has been estimated by mensuration that the river erosion which has caused the toe recession, has started in 1992.

2) The landslide deposits at the landslide toe are highly deformed internally by slow flow. The plunges of the movement vectors obtained by the control surveying are very different for different hubs. Therefore, the displacement pattern for the toe of the Lesueur landslide is not just simple translation; it also involves distortion (Sec. 5.1.3).

**Surface of Rupture and Mode of Movement**

1) The Lesueur landslide succession has translational surfaces of rupture and the Oldman has rotational surfaces of rupture. Respectively, they show compound and rotational modes of sliding. The style of activity for the Lesueur group of the landslides is either complex or composite but for the Oldman group it is multiple (Sec. 6.3).

2) The translational part of the surface of rupture (of Lesueur group of landslides) has been determined to pass through the bedrock.

3) The elevation of the surface of rupture can be bracketed, approximately, between the North Saskatchewan River level and ~ 7 m above it (Sec. 6.3).

4) The shallow movements existing on the foot of the upstream group of the landslide are suggested to have retrogressive surfaces of rupture (Sec 6.3).

Table 6.2 shows the characteristics of different landslides along the entire length of the successions (Sec.6.3). Therefore, the landslides covering the lengths of both of the landslide successions are divided into the following modes (Sec. 6.3).

a) reactivated complex compound slide (in Lesueur succession),

b) inactive complex compound slide (in Lesueur succession),

c) retrogressive multiple rotational slide (in Oldman succession)

The reasons behind having different types and sizes of landslides in the downstream and upstream segments of the study area are concluded to be ice thrusting at the Lesueur succession. Its subsequent softening of the bedrock and its bentonite seam has produced translational landslides whereas in the Oldman succession, the absence of ice thrusting has resulted in rotational landslides.

***Reference:***

Agriculture Canada, 1988. Soil salinity, 1:1000 000 Land Resources Research Center, Agriculture Canada.

Agriculture Canada, 1962. Soil survey of Edmonton sheet, 83H west half. 1: 126 720, Soil Research Institute, Ottawa.

Alberta Research Council, 1975. Bedrock topography and preglacial thalweg in the Edmonton area, 1: 50 000. Alberta Research Council, Bulletin 32.

Alberta Geological Survey, 1981. Aggregate Sources Map, 1 / 50000. Alberta Geological Survey.

Andriashek , L.D., 1988. Quaternary Stratigraphy of Edmonton Map Area, NTS 83H. Natural Resources Division, Alberta Research Council.

Andriashek, L. D. and Thomson, D.G. and Jackson R., 1997. Hydrogeology of the Edmonton Landfill, Alberta. Eyles, N., In Environmental Geology of Urban Area, Geotext 3. Geological Association of Canada, St. John.

Babcock, E.A., 1974. Jointing in Central Alberta. Canadian Journal of Earth Sciences, Vol. 11, pp. 1181 –1186.

Bayrock, L.A. and T.E. Berg, 1966. Geology of the City of Edmonton, part 1: central Edmonton. Alberta Research Council, Rept. 66-1, 30 p.

Bayrock, L.A. and G.M. Hughes, 1962. Surficial Geology of the Edmonton District. Alberta Research Council, Rept. 62-6, 40 pp.

City of Edmonton, 1991. Orthophoto map of Edmonton, 1:5000. Roadway Engineering Branch,Edmonton.

City of Edmonton, 1990. Hydrogeologic Assessment, Edmonton Waste Management

Center. Environmental Center, City of Edmonton.

Cruden, D.M., A. Peterson, S. Thomson and P. Zabeti, 1998. Lesueur Landslide: 35 Years Old and still Active. Submitted to 51st Canadian Geotechnical Conference. Geotechnical Society of Edmonton, Edmonton.

Cruden, D. M., Rains, R.B. and Thomson, S., 1993. A Short Walk in the North Saskatchewan River Valley. Field Trip Guidebook A8, Geological Association of Canada / Mineralogical Association of Canada, 40 p.

Cruden, D. M. and Thomson, S., 1987. Exercises in Terrain Analysis. Pica Pica Press, University of Alberta, Edmonton, 185 pp.

Cruden, D.M., Thomson, S., and de Lugt, J.S. 1993. A Suggested Method of Estimating Setbacks from the Crest of Slopes on the Interior Plains of Alberta. Canadian Geotechnical Journal, vol. 30, pp. 863- 875.

Cruden, D. M. and Varnes, D. J., 1996. Landslide types and processes. In Landslide, investigation and mitigation, chap.3. Transportation Research Board, Special Report 247, Washington D. C.

Davis, J.A., 1995. The Lesueur Landslide Map, 1:200. Unpublished, University of Alberta, Dept. of Civil Engineering, Edmonton.

Dewar, D., 1996. Landslides in the Mackay River Valley. M.Sc. thesis, Department of Civil Engineering, University of Alberta. Edmonton, Alberta.

Energy, Mines and Resources Canada, 1981. Frost Free Period, 1: 7 500 000. Survey and Mapping Branch, Energy, Mines and Resources Canada, Ottawa.

Energy, Mines and Resources Canada, 1981. Last frost in spring, 1: 7 500 000. Survey and Mapping Branch, Energy, Mines and Resources Canadas, Ottawa.

Energy, Mines and Resources Canada, 1981.Temperature- April and Oct., 1: 7 500 000. Survey and Mapping Branch; Energy, Mines and Resources Canals, Ottawa.

Energy, Mines and Resources Canada, 1981.Wetland map, 1: 7 500 000. Survey and Mapping Branch, Energy, Mines and Resources Canada, Ottawa.

Energy, Mines and Resources Canada, 1981.Temperature- Jan. and July, 1: 7 500 000. Survey and Mapping Branch, Energy, Mines and Resources Canada, Ottawa.

Energy, Mines and Resources Canada, 1985. First frost in autumn, 1: 7 500 000. Survey and Mapping Branch, Energy, Mines and Resources Canada, Ottawa.

Energy, Mines and Resources Canada, 1991. Precipitation, 1: 12 500 000. Survey and Mapping Branch, Energy, Mines and Resources Canada, Ottawa.

Godfrey, J.D., 1993. Edmonton Beneath our Feet: a guide to the geology of the Edmonton region. Edmonton Geological Society, Edmonton, 150 p.

Hutchinson, J.N.,1983. Methods of Locating Slip Surfaces in Landslides. Bull. of the Association of Engineering Geologists, vol.20, No. 3, pp. 235-252.

Irish, E.J.W., 1965. Geology of Rocky Mountain Foothills, Alberta. Research Council of Alberta, 68 p.

Kathol, C. P. and McPherson, R. A., 1975. Urban Geology of Edmonton. Alberta Research Council, Bulletin 32, Edmonton.

Matheson, D.S. and Thomson, S., 1973. Geological Implication of Valley Rebound. Canadian Journal of Earth Sciences, Vol. 10, pp. 961-978.

Moffitt, F. and Bouchard, H., 1987. Surveying,. Harper and Row, New York.

Nurkowski, J.R., 1984. Coal Quality, Coal Rank Variation and its relation to reconstructed overburden, Upper Cretaceous and Tertiary Plain coals, Alberta, Canada. American Assoc. of Petroleum Geologists, Bulletin 68, pp. 285-295.

Odysky, N.M., 1962, Soil zones of Alberta, scale 1/500000. Research Council of Alberta, Edmonton.

Painter, W. T., 1965. An investigation of the Lesueur landslide, Edmonton, Alberta. Unpublished M. Sc. Thesis, Dept of Civil Engineering, University of Alberta, Edmonton.

Rains, B. and Welsh, J., 1988. Out- of-phase Holocene Terraces in Part of the North Saskatchewan River Basin, Alberta. Canadian Journal of Earth Sciences, vol. 25, pp.454-464.

Sarma, S.K., 1979. Stability Analysis of Embankments and Slopes. American Society of Civil Engineers, GT 12, 105, pp. 1511-1524.

Soil Research Institute, 1962. Soil Survey of Edmonton, 1 / 1000 000. Soil Research Institute.

Tedder, K. H. 1986. Slope stability in the North Saskachewan River valley. Unpublished M.Sc. thesis, Dept. of Civil Engineering. University of Alberta, Edmonton.

Thomson, S., 1971. The Lesueur landslide, A failure in upper Cretaceous clay shale. In Proc. 9th Annual Symp. on Geology and Soil Engineering, Boise, Idaho, pp. 257-287.

Thomson, S. and Bruce, I., 1979. An air photo study of landslides along the North Saskachewan River in central Alberta, Canada. Dept. of Civil Engineering , The University of Alberta, Edmonton.

Yoon, T.N. and H. Van der Pluym, 1974. Buried channels in the Edmonton, Lac la Biche - Cold Lake area, Alberta. Groundwater Branch Rept. Alberta Environment, Edmonton, 99 p.

*Appendix A*

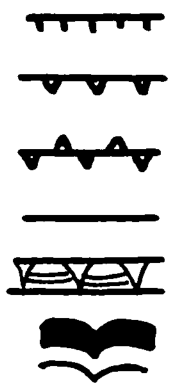
## *AERIAL PHOTO INFORMATION*

| Photo No. | Date of Photography | Represented Epoch | Scale | Focal Length | Flight Height | Identification No. | Covered Area | Source |
|---|---|---|---|---|---|---|---|---|
| | | | | (mm) | (m) | | | |
| 1 | 1952 | Before 1952 | 1 / 11600 | | N/A | LN10-AS004 | Up and Downstream part | Maps Alberta |
| 2 | 1962 | 1952-1962 | 1 / 6285 | | N/A | yc-479-81 | Upstream part | City of Edmonton |
| 3 | 1971 | 1962-1971 | 1/6389 | 152.677 | 975 | [illegible] | Upstream part | City of Edmonton |
| [illegible] | 1971 | 1962-1971 | 1/6389 | 152.677 | 975 | [illegible] | Middle part | City of Edmonton |
| 5 | 1971 | 1962-1971 | 1/6389 | 152.677 | 975 | [illegible] | Downstream part | City of Edmonton |
| 6 | 22/05/1974 | 1971-1974 | 1 / 6066 | 153.263 | 929 | NW- 16574-9E-50 | Upstream part | City of Edmonton |
| 7 | 22/05/1974 | 1971-1974 | 1 / 6066 | 153.263 | 929 | NW- 16574-9E-52 | Middle part | City of Edmonton |
| 8 | 22/05/1974 | 1971-1974 | 1 / 6066 | 153.263 | 929 | NW- 16574-8W-86 | Downstream part | City of Edmonton |
| [illegible] | 08/05/1976 | 1974-1976 | 1/5012 | 153.263 | 768 | [illegible] | Upstream part | City of Edmonton |
| 10 | 08/05/1976 | 1974-1976 | 1/5012 | [illegible] | 768 | [illegible] | Middle part | City of Edmonton |
| [illegible] | 08/05/1976 | 1974-1976 | 1/5012 | [illegible] | 768 | [illegible] | Downstream part | City of Edmonton |
| 12 | 10/05/1980 | 1976-1980 | 1 / 5407 | 152.199 | 823 | L25E-FF8018-51 | Upstream part | City of Edmonton |
| 13 | 10/05/1980 | 1976-1980 | 1 / 5407 | 152.199 | 823 | L25E-FF8018-53 | Middle part | City of Edmonton |
| 14 | 10/05/1980 | 1976-1980 | 1 / 5407 | 152.199 | 823 | L26W-FF8019-237 | Downstream part | City of Edmonton |
| [illegible] | 17/05/1982 | 1980-1982 | [illegible] | [illegible] | 792 | [illegible] | Upstream part | City of Edmonton |
| 16 | 17/05/1982 | 1980-1982 | [illegible] | [illegible] | 792 | [illegible] | Middle part | City of Edmonton |
| [illegible] | 17/05/1982 | 1980-1982 | [illegible] | [illegible] | 792 | [illegible] | Downstream part | City of Edmonton |
| 18 | 21/06/1984 | 1982-1984 | 1 / 5270 | 153.260 | 807 | L31W-NW-36684-82 | Upstream part | City of Edmonton |
| 19 | 21/06/1984 | 1982-1984 | 1 / 5270 | 153.260 | 807 | L31W-NW-36684-80 | Middle part | City of Edmonton |
| 20 | 21/06/1984 | 1982-1984 | 1 / 5270 | 153.260 | 807 | L32W-NW-36684- | Downstream part | City of Edmonton |
| [illegible] | [illegible] | 1984-1986 | [illegible] | [illegible] | 823 | [illegible] | Upstream part | City of Edmonton |
| 22 | [illegible] | 1984-1986 | [illegible] | [illegible] | 823 | [illegible] | Middle part | City of Edmonton |
| [illegible] | [illegible] | 1984-1986 | [illegible] | [illegible] | 823 | [illegible] | Downstream part | City of Edmonton |
| 24 | 06/10/1988 | 1986-1988 | 1 / 5279 | 153.016 | 808 | L31E-AS-3775-63 | Upstream part | City of Edmonton |
| 25 | 06/10/1988 | 1986-1988 | 1 / 5279 | 153.016 | 808 | L31E-AS-3775-65 | Middle part | City of Edmonton |
| 26 | 06/10/1988 | 1986-1988 | 1 / 5279 | 153.016 | 808 | L32E-AS-3775-142 | Downstream part | City of Edmonton |
| [illegible] | 31/05/1990 | 1988-1990 | 1/5210 | 153.103 | 792 | [illegible] | Upstream part | City of Edmonton |
| 28 | 31/05/1990 | 1988-1990 | 1/5210 | 153.103 | 792 | [illegible] | Middle part | City of Edmonton |
| 29 | 31/05/1990 | 1988-1990 | 1/5210 | 153.103 | 792 | [illegible] | Downstream part | City of Edmonton |
| 30 | 24/10/1992 | 1990-1992 | 1 / 5234 | 151.402 | 792 | L31E-ED9211-66 | Upstream part | City of Edmonton |
| 31 | 24/10/1992 | 1990-1992 | 1 / 5234 | 151.402 | 792 | L31E-ED9211-68 | Middle part | City of Edmonton |
| 32 | 24/10/1992 | 1990-1992 | 1 / 5234 | 151.402 | 792 | L32E-ED9211-144 | Downstream part | City of Edmonton |
| 33 | 13/05/1995 | 1992-1995 | 1/5117 | 303.792 | 1554 | [illegible] | Upstream part | City of Edmonton |
| 34 | 13/05/1995 | 1992-1995 | 1/5117 | 303.792 | 1554 | [illegible] | Middle part | City of Edmonton |
| 35 | 13/05/1995 | 1992-1995 | 1/5117 | 303.792 | 1554 | [illegible] | Downstream part | City of Edmonton |
| 36 | 13/05/1997 | 1995-1997 | 1 / 5117 | 303.792 | 1554 | L31E-ED9711-68 | Upstream part | City of Edmonton |
| 37 | 13/05/1997 | 1995-1997 | 1 / 5117 | 303.792 | 1554 | L32E-ED9711-145 | Downstream part | City of Edmonton |

*Appendix B*

# *AERIAL PHOTO INTERPRETATION*

**LEGEND** (for aerial photos)



Scarp

Break in slope

Horst

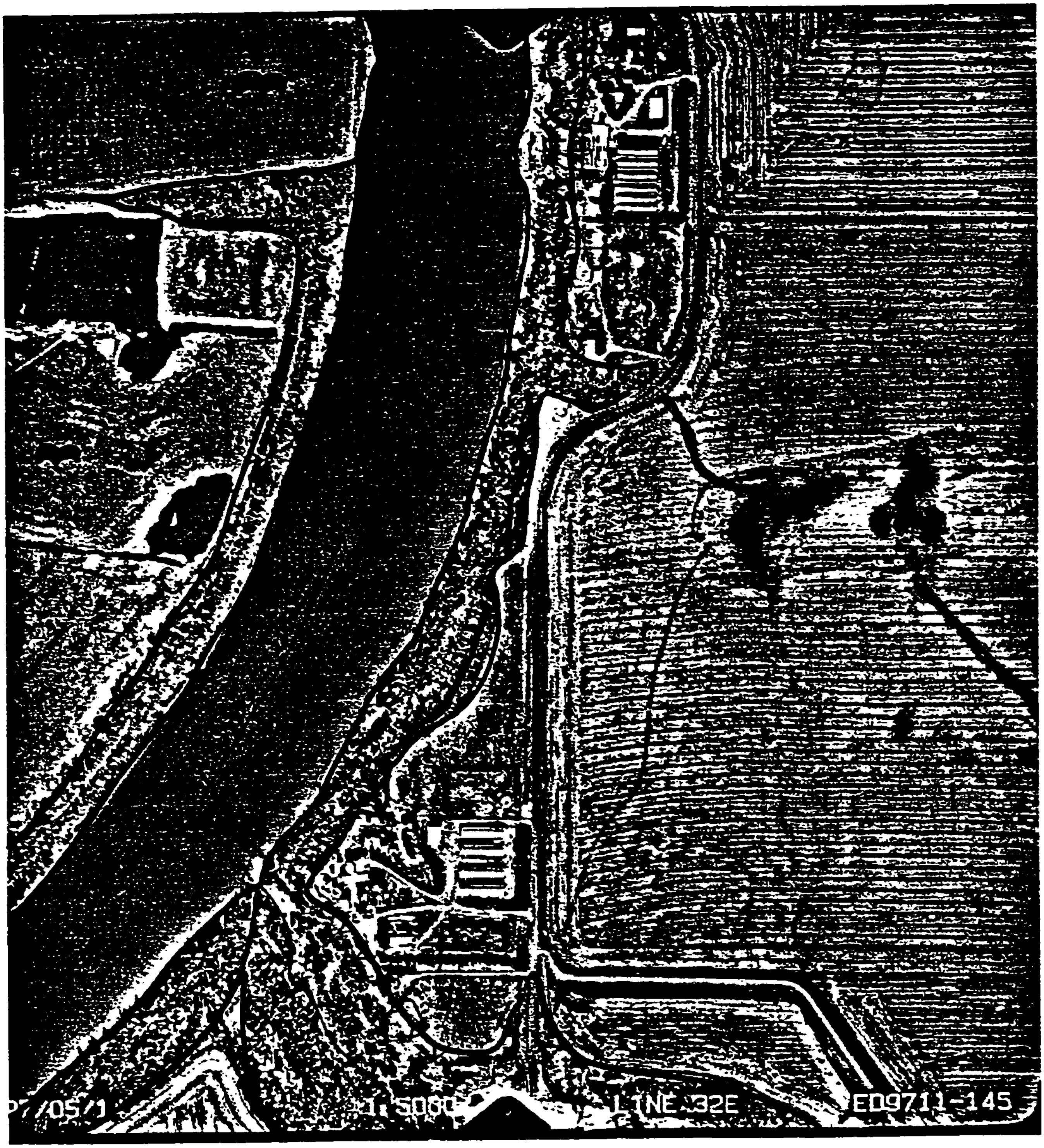
River edge

Slope > 45 °

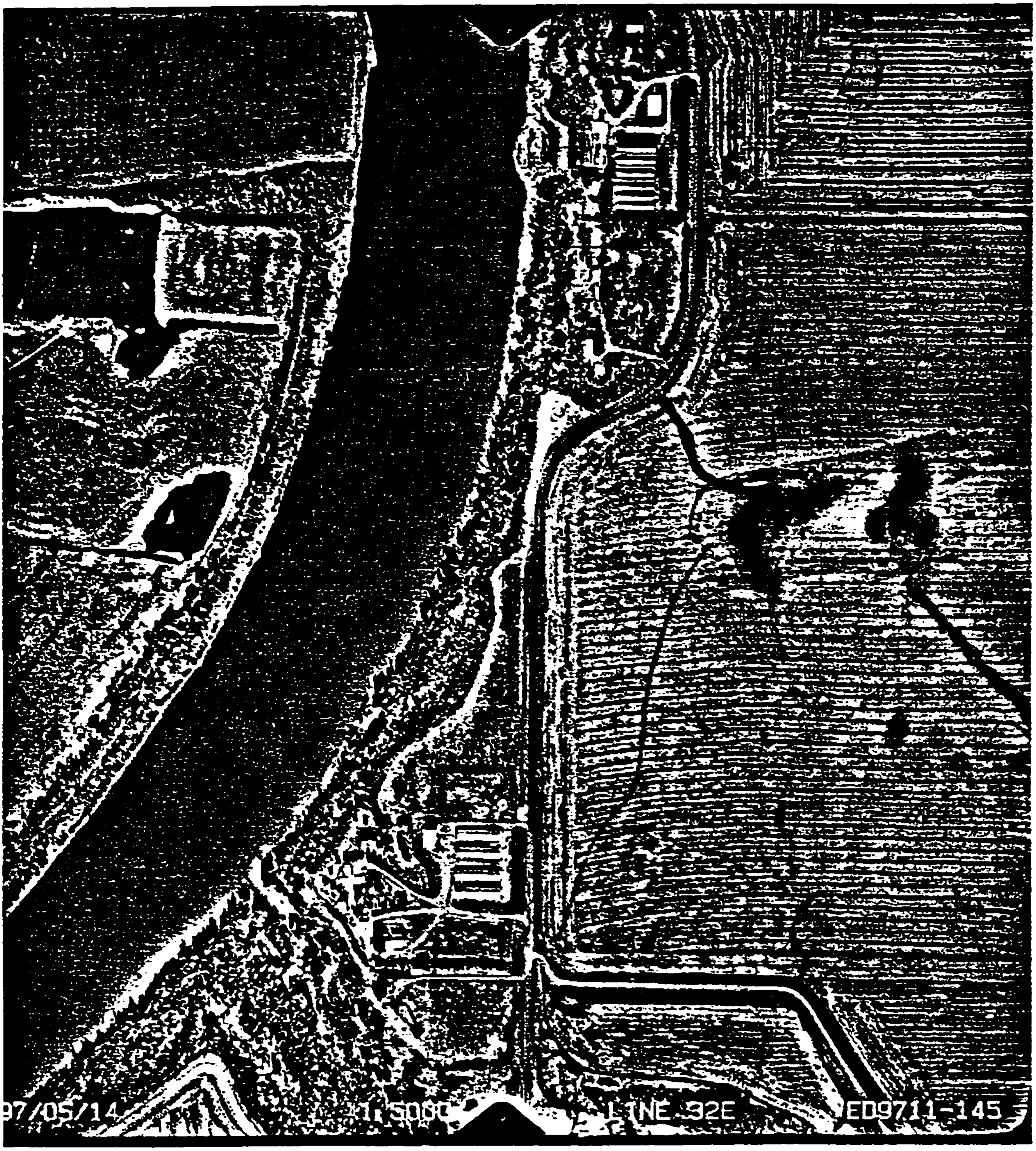
Terrace

The following are copies of two aerial photos (1997) which their index numbers for this study are 36 and 37.


87/05/13
1:5000
ED9711


LINE 32E
ED9711-145


97/05/13
1:5000
LINE 31E
ED9711-


97/05/14
1:5000
LINE 32E
ED9711-145

*Appendix C*

## *CONTROL SURVEYING DATA*

*Raw Data of the Control Surveying*

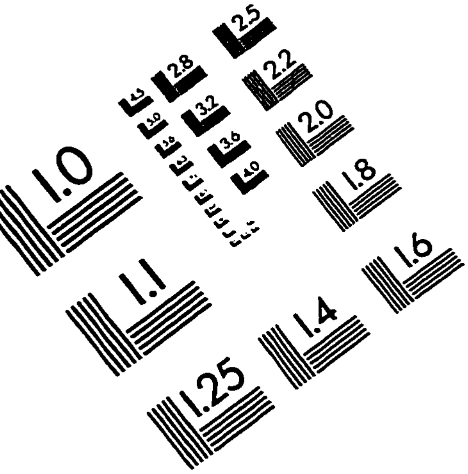
| | DISPLACEMENT (m) | | |
|---|---|---|---|
| **Hub** | **Y ( N-S direction)** | **X ( E-W direction)** | **Z ( vertical)** |
| 22 | [illegible] | [illegible] | [illegible] |
| | [illegible] | [illegible] | [illegible] |
| | [illegible] | [illegible] | [illegible] |
| | | | |
| 15 | [illegible] | [illegible] | [illegible] |
| | [illegible] | [illegible] | [illegible] |
| | [illegible] | [illegible] | [illegible] |
| | | | |
| 16 | 9865.5848 | 10307.5028 | 609.2551 |
| | 9865.5600 | [illegible] | 609.2299 |
| | [illegible] | [illegible] | 609.2385 |
| | | | |
| R6 | [illegible] | [illegible] | [illegible] |
| | [illegible] | [illegible] | [illegible] |
| | [illegible] | [illegible] | 609.1162 |
| | | | |
| R7 | [illegible] | [illegible] | [illegible] |
| | [illegible] | [illegible] | [illegible] |
| | [illegible] | [illegible] | 610.0268 |
| | | | |
| 15A | 9850.25[illegible] | 10295.[illegible] | 608.0805 |
| | 9850.3208 | 10295.5653 | 608.0509 |
| | 9850.7645 | 10295.3671 | 607.8401 |
| | | | |
| BK | [illegible] | [illegible] | [illegible] |
| | [illegible] | [illegible] | 616.4690 |
| | [illegible] | [illegible] | 616.4541 |

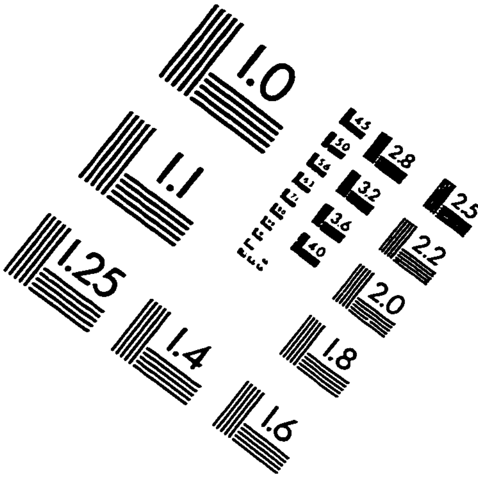
The following table is introduced for future references. It contains UTM numbers (zone 12) of hubs and the control points, which are located on the upland area of the Lesueur landslide.

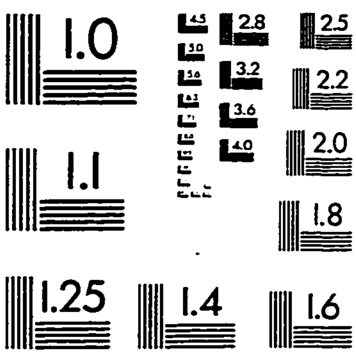
UTM Numbers of the Control Points and Hubs. For the locations of the control points and hubs refer to Davis' map (1995)

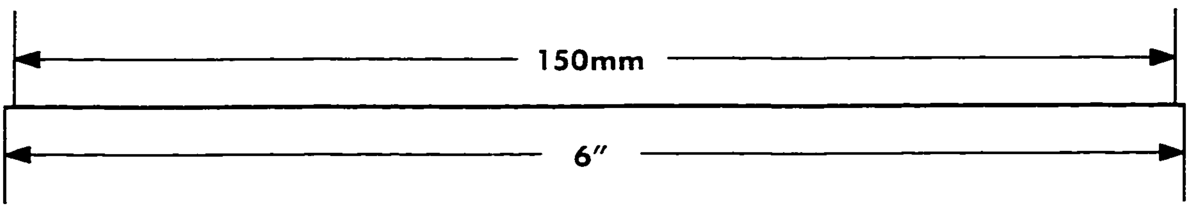
| | UTM (Zone 12) | | | |
|---|---|---|---|---|
| Control Points or Hubs | *Surveying Date* | *Northing* | *Easting* | *Elevation (m.a.s.l.)* |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | | | |
| OF | Aug. 98 | [illegible] | [illegible] | [illegible] |
| | | | | |
| Pipeun (Awn) | Aug. 98 | [illegible] | [illegible] | [illegible] |
| | | | | |
| Hub 22 | Oct. 96 | [illegible] | [illegible] | [illegible] |
| | May 97 | [illegible] | [illegible] | 610.392 |
| | Oct. 97 | [illegible] | [illegible] | 610.256 |
| | Aug. 98 | [illegible] | [illegible] | 610.225 |
| | | | | |
| Hub 15 | Oct. 96 | [illegible] | [illegible] | [illegible] |
| | May 97 | [illegible] | [illegible] | 611.888 |
| | Oct. 97 | [illegible] | [illegible] | [illegible] |
| | Aug. 98 | [illegible] | [illegible] | [illegible] |
| | | | | |
| Hub 16 | Oct. 96 | [illegible] | [illegible] | 609.265 |
| | May 97 | [illegible] | [illegible] | 609.240 |
| | Oct. 97 | [illegible] | [illegible] | 609.249 |
| | Aug. 98 | [illegible] | [illegible] | 609.170 |
| | | | | |
| Hub R6 | Oct. 96 | [illegible] | 347025.132 | 609.451 |
| | May 97 | [illegible] | [illegible] | 609.427 |
| | Oct. 97 | [illegible] | [illegible] | [illegible] |
| | Aug. 98 | [illegible] | [illegible] | [illegible] |
| | | | | |
| Hub R7 | Oct. 96 | [illegible] | [illegible] | 609.988 |
| | May 97 | [illegible] | [illegible] | 609.976 |
| | Oct. 97 | [illegible] | [illegible] | [illegible] |
| | Aug. 98 | [illegible] | [illegible] | [illegible] |
| | | | | |
| Hub 15A | Oct. 96 | [illegible] | [illegible] | 608.091 |
| | May 97 | [illegible] | [illegible] | 608.071 |
| | Oct. 97 | [illegible] | [illegible] | 607.851 |
| | | | | |
| D3 (pipe) | Oct. 96 | [illegible] | [illegible] | 616.496 |
| | May 97 | [illegible] | [illegible] | 616.480 |
| | Oct. 97 | [illegible] | [illegible] | 616.465 |

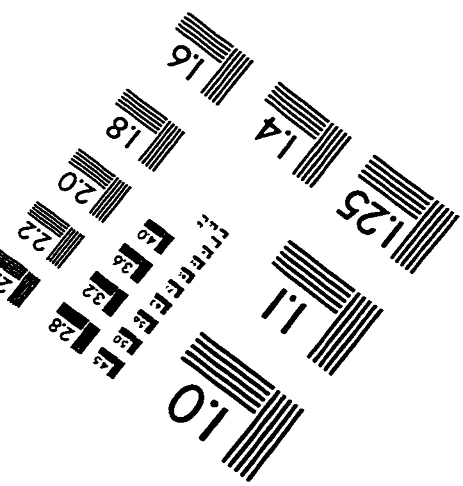
# IMAGE EVALUATION TEST TARGET (QA-3)

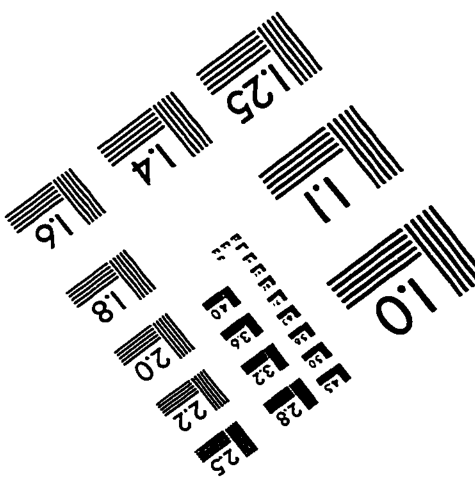










APPLIED IMAGE . Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989