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Landslides in the Morkill River Valley, British Columbia

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Landslides in the Morkill River Valley, British Columbia submitted by Corey Raymond Froese in partial fulfillment of the requirements for the degree of Master of Science.
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ABSTRACT

Operational and construction problems in forestry developments in a valley in the Canadian Rockies are associated with landslides in weakly cemented lake sediments. The landslides have been inventoried. The undisturbed sediments contain up to 11 % calcium carbonate and are susceptible to softening by mechanical and chemical weathering processes.

Chemical weathering by leaching and dissolution of the calcite cement is documented in the field by obtaining density profiles and observations of relative effervescence and quantified in the laboratory program. There is a linear relation in the increase in density with increase in carbonate content in the field profiles. Unconfined Compression Tests on field samples subjected to cycles of freeze and thaw showed a 50 % decrease in strength after only one cycle.

The softening process leads to a decrease in shear strength and surficial landslides, composite earth slide-earth flows, in the silty soils and earth slides in the sandy soils.

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Chapter 1: Introduction

Some operational and construction problems in forestry developments in a valley in the Canadian Rockies are associated with surficial landslides in lake silts. Although landsliding in the valley is not rapid or deep, it challenges construction to reduce sediment deposition into salmon spawning streams from both natural and constructed cut and fill slopes. Concerns of environmental and government agencies were a driving force in the initiation of this study into the geotechnical properties, distribution and landslide mechanisms of the weakly cemented soils of the Morkill River Valley. The objectives of this study, as outlined in a research contract with the British Columbia Ministry of Forests, are as follows:

1) To compile data on the areal frequency and causes of landslides in the Morkill drainage.
2) To catalogue identified slides as to processes and collect data at representative landslides, both natural and logging-related.
3) To undertake limited laboratory and field testing and geotechnical analysis to determine which soil strength properties govern the stability of landslides. This will provide a sound engineering basis for input variables into any probabilistic analysis.
4) To provide a methodology for developing a probabilistic model for assessing relative frequencies of landslides for terrain stability mapping, detailed site surveys and terrain attribute studies that incorporate soil strength properties and contributing factors both human and natural.
5) Assess the usefulness of various road construction techniques in reducing landslide initiation.

I begin the study with a review of the existing literature on cementation (Chapter 2) concentrating on calcium carbonate cement and its effects on the properties of soils. The literature review then further concentrates on the evidence of calcium carbonate cementation in the soils of Western Canada and its relation to soluble bedrock sources outlined in the geological literature.

I initiate the specific work in the Morkill River valley with a preliminary office study of existing maps, climatic data and air photos of the study area (Chapter 3). The purpose of this study is to identify the types and distribution of landsliding in the Morkill River valley and to begin planning the field mapping program.

Once in the field, I visited accessible landslide locations highlighted in the office study (Chapter 3) and undertook a field landslide inventory. This was undertaken to gather information on the site-specific characteristics of landslides in the Morkill River valley (Chapter 4). Landslide inventory tables and airphotos presented in Appendices A and B, provide a visual reference for the landslide inventory work. During the field program I also undertook an inventory of soil and bedrock exposures in order to gather information as to the vertical and lateral extent of lacustrine deposits in the Morkill River valley and to establish the different levels of lake sediments and their history of deposition (Chapter 4).

I undertook density testing and visual carbonate quantification in order to gather information on the relation between the calcium carbonate content and the density in the soils across the valley (Chapter 5). A laboratory testing program (Chapter 6) to determine the index properties of the lacustrine sediments (grain size, Atterberg limits) used these test results to assess the frost susceptibility and segregation potential of the soils. Unconfined compression tests on samples subjected to alternating cycles of freeze and thaw ascertained the effects of thaw weakening on the soils. I supplemented the field calcium carbonate observations with a detailed analysis of the carbonate contents of all samples that I obtained during the field program. To further evaluate the form in which the calcium carbonate was found in the soils tested, scanning electron microscopy was utilized.

Once testing on the field samples was completed, I applied the results to the observations taken during the field investigation (Chapter 7). I then described the types of landslides in the Morkill River valley and their postulated failure mechanisms. The results of the laboratory testing are further utilized to corroborate the field observations of potential landslide mechanisms.

One of the aims of this study is to provide a methodology for developing a probabilistic model for assessing relative frequencies of landslides for terrain stability mapping, detailed on site surveys and terrain attribute studies that incorporate soil strength properties and contributing factors, both human and natural. Chapter 8 summarizes the characteristics of the lake deposits and addresses the performance of cuts in the soils of the Morkill River valley.

Chapter 9 summarizes the findings of the thesis and provides recommendations for possible future studies.

Chapter 2: Literature Review

2.1 Introduction

Calcite cementation in soils has long been identified by soil scientists who routinely describe the calcareousness of soils in the field and laboratory and address the effects of the cementation on soil nutrients and performance of plants and trees. Although the effects of calcite cementation are not commonly identified by geotechnical engineers in practice, quantitative links between carbonate content and geotechnical soil properties have been addressed.

Since the 1950's, geotechnical engineers have made attempts to quantify the effects of cementation on the geotechnical properties of soils. Qualitative correlations as to the effects of carbonate cementation on void ratio, apparent preconsolidation pressures and undrained shear strength have been made to this point. Quantitative correlations are dependent on several factors such as grain size, mineralogy, stress history and are therefore not well understood to date.

Studies of the geotechnical properties of calcareous soils in Western Canada are not widespread. Studies in the soil science literature were found for an area in the Canadian Rockies. In Alberta, studies as to the origin and distribution of calcium carbonate-rich marl and tufa deposits have been published. As well, studies highlighting the carbonate cementation in the lacustrine silts of the South Thompson and Columbia Lake regions, and the sensitive glaciomarine sediments of the Terrace-Kitimat area, have been reviewed.

2.2 *Geotechnical Properties of Weakly Cemented Sediments*

Boone and Lutenegger (1997) described the effects of carbonate cementation on the geotechnical properties of glacially derived sediments in eastern Ontario and New York State. Perhaps the most important contribution of this work was the very detailed summary of the effects of calcite cementation.

Carbonate cementation has long been realized to have an effect on the geotechnical properties of soils. Cementation has been cited in creating apparent preconsolidation pressures, brittle behavior, increased strength and increased sensitivity (Boone and Lutenegger, 1997). Demars and Chaney (1982, p. 400) stated that carbonates "..are among the few mineral cemented agents capable of converting loose aggregate into rock.." Even though numerous qualitative observations such as Demars and Chaney's have been made, strong quantitative correlations between geotechnical properties and carbonate content have not been established to date.

Perhaps the furthest advances in quantitative recognition of the effects of carbonate cementation have been made in relations to the preconsolidation (McKown and Ladd, 1982; Jamiolkowski et al., 1985; Burghignoli et al, 1991; and Boone and Lutenegger, 1997). Studies by Fischer et al. (1978) of the effects of artificial cementation on preconsolidation and overconsolidation ratio (OCR) found that increases in $CaCO_3$ of 2.2-3.9 % produced an apparent OCR of 1.7. The main reason is that the soils have a higher apparent stiffness due to the bonds produced by the cementation. These bonds have been identified as producing a rounded e-log p plot, similar to overconsolidated soils. Based on these findings, Boone and Lutenegger (1997) stated that cementation likely formed an integral part of soil behaviour, even for those deposits that were traditionally considered overconsolidated based on oedometer test results.

Another important impact of carbonate cementation was its effect on shear strength and sensitivity in glacially derived sediments. Mitchell (1993) listed both cementation and leaching of salt (in glacial marine clays) as mechanisms producing soil sensitivity. Mitchell (1993) states that the disturbance of cementation bonds led to loss of strength. Leaching, although it caused little change in fabric, changed interparticle forces and resulted in a decrease in undisturbed strength of up to 50 percent (Mitchell, 1993).

The effects of cementation on shear strength were discussed by Lambe (1960) and Bjerrum and Wu (1960) who described cementation of particles as a component of the shear resistance. Studies to quantitatively demonstrate this were further carried out in the 1970's. Loisell et al (1971) addressed the effects of removal of cementation by artificially leaching 0.43 % of Fe^{3+} and 0.22 % of Ca^{2+} from a soil with a corresponding decrease in undrained shear strength of 10-20 %. The effects of the artificial precipitation of calcium carbonate were then studied by Fischer et al. (1978). Fischer et al. (1978) recorded an increase in the undrained shear strength of a Drammen Clay of 30-40% and an increase in secondary consolidation of 10-15 % due to the artificial precipitation. Since this time, attempts have been made to provide a direct correlation between shear strength and carbonate content. Boone and Lutenegger (1997) and others stated that there has been no relation developed between carbonate content and shear strength developed because there is alteration of the specimens during sampling and consolidation processes (Adams and Radhakrishna, 1970; Conlon and Isaacs, 1970; La Rochelle and Lefebvre, 1970; La Rochelle et al., 1976) and that the variation of carbonate content within a sample will influence the observed laboratory values of undrained shear strength. McKown and Ladd (1982); Birrhignoli et al, (1991) have shown cementation produced considerable increases in the vertical effective stress over short depth intervals as a result of the relatively low values of void ratio obtained in cemented soils. For these reasons, quantitative relations between natural cementation and shear strength remain undefined.

Although there remains a gap in the knowledge of quantitative effects of carbonates on shear strength, qualitative studies of the natural removal of carbonates by leaching have been undertaken. For many years, researchers have studied the effects of the salinity of pore water on Norwegian glacial marine clays and the Leda clays of eastern Canada (e.g., Rosenqvist, 1953, 1955, 1963, 1966; Bjerrum and Rosenqvist, 1956; Kenney et al, 1967; Torrance, 1975). Quigley (1980) suggested a qualitative correlation between total carbonate content and sensitivity. Boone and Lutenegger (1997) suggested that the effect of carbonate cementation on vertical effective stress is much less in marine soils than in lacustrine soils. Boone and Lutenegger (1997, p.544) also stated " although salt flocculation-leaching likely dominates the development of sensitivity in the marine deposits, relatively high carbonate contents and subsequent cementation may be a significant contributor to the enigmatic differences in sensitivity between Norwegian and Canadian quick clays."

Studies of the leaching of calcite have been described by Merrit and Muller (1959), Dreimanis (1961), Quigley and Ogubadejo (1972b), and Lutenegger (1995). Hawkins and McDonald (1992) indicated that leaching of calcite, by either seepage flow or seepage combined with natural acids caused by biodegradation or weathering, may be a cause for slope instability. Boone and Lutenegger (1997, p.544) stated that " Carbonate leaching from seepage may be an important mechanism in reducing shear strength and creating slope instability , both as mechanisms in surficial soils and in deeper failure of deposits with layers of higher permeability." The effects and mechanics of leaching are discussed in Chapter 7.

2.3 Carbonate Sediments in Western Canada

Published studies of the geotechnical properties of weakly cemented soils in Western Canada are not common in the geotechnical literature. Studies in the geoscience literature as to the location of carbonate bedrock (Ford, 1989); landslides in carbonate bedrock (e.g., Cruden 1987, McAffee and Cruden, 1996); and locations of deposits of calcareous marl and tufa (Macdonald, 1982) have been undertaken to date. In the soil science literature, studies as to the occurrence of calcite cemented soils have been related to forestry activities (Smith and Was, 1994a,b). In the 1970's, the British Columbia Ministry of Highways completed studies regarding the geological hazards associated with weakly cemented sediments in the Columbia Lakes and South Thompson/Penticton Regions of British Columbia (Haughton, 1978; Nyland and Miller, 1976). More recently, published studies by Geertsema and Schwab (1997, 1995a,b,c) have highlighted the occurrence of calcium carbonate as a cementing agent in the glaciomarine sediments of the west coast of British Columbia near Kitimat and Terrace.

Ford (1989, Figure 9.34) illustrated the distribution of carbonate and other soluble rocks in Canada; gypsum, limestone and dolomite outcrop over approximately 1.25 million km^2 of Canada. As the rocks described by Ford are soluble, carbonate precipitates may be associated with sediments found in these areas. The areas shown include the present study area, the studies undertaken by Boone and Lutenegger (1997) in eastern Ontario, the studies in the Canadian Rockies near Golden, British Columbia, by Smith and Wass (1994a,b), and the BC Ministry of Highways studies in the Columbia Lakes and South Thompson Regions (Haughton, 1978; Nyland and Miller, 1977).

In Alberta, the nature and distribution of marl and tufa deposits were reported by Macdonald (1982) as resources in the agriculture sector for treatment of acidic soils. Marl was defined as greater than 50 percent Calcium Carbonate Equivalence (C.C.E), while tufa was defined as greater than 80 percent C.C.E. Both marl and tufa are precipitated from calcium carbonate-rich groundwater discharge, often in the form of springs originating from limestone bedrock. Tufa deposits associated with springs in Alberta (Borneuf, 1982) and in the Rocky Mountains (Gadd, 1986) were described in the literature. Extensive deposits of marl and tufa in Alberta were identified by Macdonald (1982) with volumes in excess of one hundred thousand cubic metres.

Since the 1950's, the occurrence of calcium carbonate has been identified as a cementing agent in the silts of the South Thompson Region of British Columbia. Hardy (1950) attributed the subsidence of about 1-0.75 inches (19-25 centimetres) per foot (30 centimetres) in the Kamloops silts to the collapse of the internal soil structure after the dissolution of calcium carbonate bonds in the silt.

For studies by the BC Ministry of Highways and Public Works (Highways) on the lacustrine silt deposits of the Columbia Lake area (Haughton, 1978) and the South Thompson/Penticton area (Nyland and Miller, 1977) laboratory testing conducted by Quigley (1976) identified 7 to 8 % calcium carbonate content in the glaciolacustrine silts. Quigley (1976, p. 16) stated: " Small amounts of soluble precipitates or evaporites were found. These are significant in that evaporites occurring at the points of contact between silt grains can have a marked effect on the decrease in stability of the silt structure upon wetting."

Smith and Wass (1994a,b) published two reports for the Pacific Forestry Centre concerning the impacts of skid roads and stump uprooting on the properties of calcareous loamy soils in Golden, British Columbia. Although the studies were primarily concerned with the effects of soil disturbance on planted seedling performance, results as to the carbonate content, soil type and insitu densities were provided. Smith and Wass (1994a,b) reported on the densities of a sandy silt with some clay with low free carbonates (2-8 %). Bulk densities reported in these sediments ranged from 1.07 Mg/m^3 within the top 0 to 10 cm to 1.81 Mg/m^3 at a depth of 60-70 cm.

Over the last few years, studies of the retrogressive flow slides in sensitive glaciomarine sediments in the Kitimat-Terrace region have been published (Geertsema and Schwab, 1997, 1995a,b,c). The soils outlined by Geertsema and Schwab (1997) consisted of predominantly silt sizes that consisted of glacially ground quartz, feldspar, illite and chlorite. These mineralogies were consistent with those in the sensitive glaciomarine sediments found in eastern Canada and Scandinavia (Geertsema and Schwab, 1997). A detailed study of old landslide scars in the Kitimat-Terrace area looked at the ages of the landslides by carbon dating and the effects of leaching on the calcium carbonate content. Geertsema and Schwab (1997) noted that calcium carbonate was found in deep soil deposits and in surficial deposits of relict landslides; low pH values were indicative of the neutralization of calcium carbonate, originally up to 5% by volume, by acids produced from decaying organic matter over time. Observations of the porewater in the study areas exhibited very low concentrations of Na^+, Ca^{2+} , K^+ and Mg^{2+} , further indications that the majority of leaching had already occurred (Geertsema and Schwab, 1997).

2.5 Conclusions

Studies of the effects of calcium carbonate cementation on the geotechnical properties to date have yielded mostly qualitative correlations. Advances to date have attempted to quantify the effects of carbonate cementation on geotechnical properties and have found an increased apparent preconsolidation pressure, lower void ratio, higher undrained shear strength and increased sensitivity. Laboratory testing of the artificial removal and addition of calcite has further substantiated qualitative observations. The majority of the studies on the removal of cations by leaching have been carried out concerning the leaching of salt from glacial marine sediments in Eastern Canada and Scandinavia.

Within the last 25 years, studies concerning the location and index properties of calcareous sediments in Western Canada have appeared in the literature. When compared to Ford's (1989) map showing the occurrence of soluble rock in Canada, there is a direct correlation between the occurrence of soluble bedrock and carbonate sediments across the country. This highlights the likelihood that a large portion of the glacial lake sediments in Western Canada overlying soluble rocks contain at least a small amount of cement, carbonate or otherwise.

Chapter 3: Preliminary Office Study/Landslide Inventory

3.1 Introduction

The Morkill River is located in a valley on the western slopes on the Canadian Rocky Mountains and is subject to the extreme fluctuations in temperature and precipitation thoughout the year common in mountainous regions. The climatic effects are hypothesized to have an impact on the weathering of soils and subsequent slope instability. Concerns with respect to landsliding and sedimentation associated with forestry activites in the study area brought about a report by the Morkill Watershed Task Group (Beaudry, 1997) recommending initiation of a study into landsliding in the Morkill River watershed.

The study begins by gathering available information as to the topography, climate and geology of the Morkill River area. These data were used to assess the effects of climate on the soils of the valley. A reconnaissance level study of available airphotos was undertaken to assess the extent and distribution of landsliding in the Morkill River Valley.

3.2 Location of Site

The Morkill River is a tributary to the Fraser River with the confluence located in the vicinity of the settlement of Crescent Spur, which is 50 kilometres northwest of the town of McBride, British Columbia. This area is located in the Park Ranges of the Rocky Mountains in British Columbia (Figure 3.1).

The study area is located on National Topographic System (NTS) 1:50,000 scale map sheets 93H9, 93H10 and 83E12. The latitude of the site is between 53°20' and 53°45'N , while the longitude of the site is located between 119° 45' and 121° W.

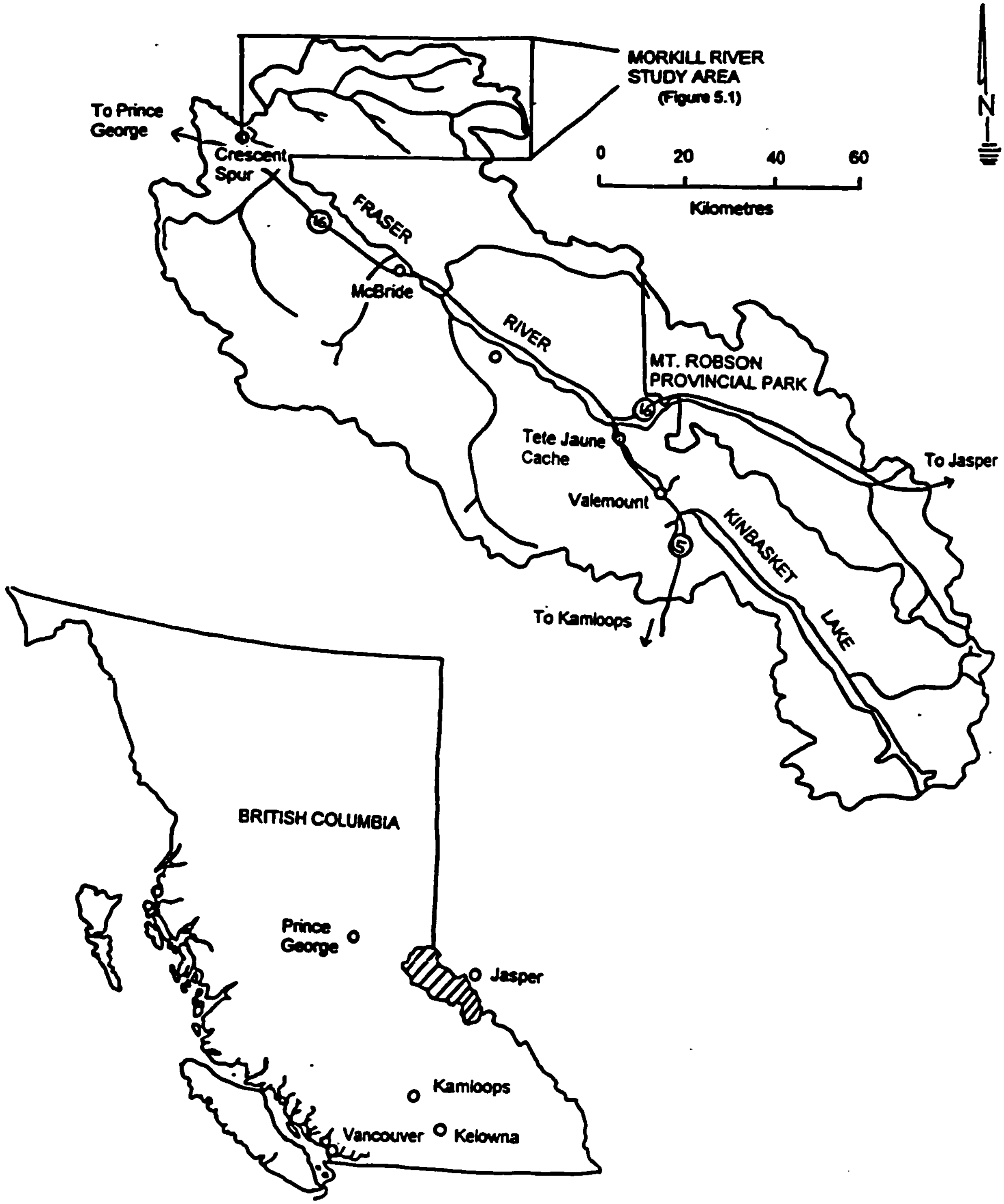


Figure 3.1 Location plan for Morkill River study area

The Morkill River itself is 85 km (53 miles) in length with an elevation gain of 1310 m from the Fraser River confluence (670 m.a.s.l.) to its headwaters adjacent to the border of Alberta's Wilmore Wilderness Provincial Park (1980 metres). The maximum elevation in the study area is 2451 m.a.s.l. atop Intersection Mountain along the Alberta - British Columbia border.

3.3 *History of Investigation*

The study of landslides in the Morkill River Valley was originally proposed by Carl Erickson, P.Eng., and Brent Ward, Ph.D., P.Geo. of the Prince George Forest Region. The delivery of sediment into the Morkill River and its tributary creeks from road construction and landsliding was of concern and the Department of Fisheries and Oceans and the Morkill River Environmental Task Group had highlighted the sediment delivery as a priority action. In January of 1997, the Morkill Watershed Task Group (Beaudry, 1997) made recommendations with respect to the management of the Morkill River watershed. Among those recommendations was to support this study.

In order that I could get a first hand look at the problems and practices in the Morkill River valley, I was taken on an initial field visit by personnel from the Prince George Forest Region and the Robson Valley Forest District in August of 1996. This visit highlighted the occurrence of fine grained lacustrine sediments and the difficulties associated with road construction in these sediments. Erosion and shallow landsliding were noted to be the major sources of sediment generation in the valley.

I began the office study with the acquisition of available topographic maps, surficial geology maps, bedrock geology maps and airphoto coverage of the Morkill River watershed.

Topographic maps of the Morkill River study area were available at scales of 1:250,000 and 1:50,000 from the Federal Government, and at scales of 1:20,000 by the British Columbia Provincial Government. As stated previously, the study area is covered by 1:250,000 map sheets 93H and 83H; 1:50,000 map sheets 93H9, 93H10, 83H12; and 1:20,000 Terrain Resource Inventory Mapping (TRIM) map sheets 93H076-060,067-070, 078-080 and 83E061-062 and 071.

In order to plan the field investigation, the 1:20,000 TRIM maps were supplemented with 1:20,000 scale Forest Development Plan Maps provided by the forestry companies operating in the study area: Zeidler Forest Products Ltd. and Slocan Forest Products Ltd. The 1:20,000 maps had the advantage of greater detail and 10 metre contours as opposed to the 100 foot (30 metre) contours on the 1:50,000 NTS map sheets. The forest development plan maps have the advantage of showing the location of all current, deactivated and proposed roads and cutting blocks in the study area. I transferred this information to the 1:20,000 TRIM maps using a light table in order to plan access to landslide locations during the field program.

Both published and non-published surficial geology maps of the Morkill River study area are currently available. A set of 1:50,000 surficial geology maps is available from the British Columbia Ministry of Environment (BCMOE)(Ryder, 1979) covering the following NTS map areas: 93H 9, 10, 14, 15, 16 and 93I 1, 2, 7, 8. I consulted these maps during the initial landslide inventory work to confirm my interpretations of the surficial geology. Surficial geology maps at a scale of 1:20,000 prepared by Geowest Environmental Consultants (Geowest, 1994) is also available but not published. These maps were not available to me during the initial office study, but were consulted during the field investigation.

The available bedrock geology map of the Morkill River study area is the 1:250,000 sheet produced by Campbell et al (1973). This level of mapping is thought to provide a good general overview of the expected bedrock types and distribution in the study area. Comments as to the accuracy of this mapping are made in Chapter 4.

3.4 Climate and Its Effects

The Morkill River study area is exposed to extreme fluctuations in climatic conditions typical of mountain environments in the Canadian Rocky Mountains. In order to characterize the seasonal climatic variability in the Morkill River area, it would be ideal to have temperature and precipitation data from within the valley itself. Although there is a small weather station in the valley at this time, the system has only been in operation for the past year and has not functioned properly during that time. Therefore, climatic information from within the valley is not available for this study.

Although not in the study area, there are a number of operating weather stations in the region monitored by Environment Canada (1981a,b). Thirty-year averages of temperature and precipitation data from these stations are presented below in Tables 3.1 and 3.2 respectively. For the purposes of this study, the climate data from the three closest climatic stations are considered to provide a reasonable representation of the climatic conditions in the Morkill River Valley.

As there is significant relief in the Morkill River watershed, there will be a corresponding decrease in temperature with increasing elevation. The Glossary of Geology gives the thermal gradient as -0.6 °C for every 100 m increase in elevation (Bates and Jackson, 1987). Based on this thermal gradient or lapse rate, the temperature variation from the lower Morkill River valley to the highest elevation at 2,451 m.a.s.l would be up to -10 °C. Therefore when compared to the average temperatures provided in Table 3.1, the highest average temperatures at the upper elevations would expected to be 5 °C with corresponding minimum average lows of -20 °C. The corresponding mean annual air temperature would then be -6 °C for the maximum elevations. This seems reasonable as snow and ice remain in the upper elevations for the entire year. The calculated estimates of temperature at the upper elevations of the Morkill River watershed are given in Table 3.1.

As a check of the temperature calculations, I made observations of the tree line elevation from the air photos and maps of the Morkill River valley and used this elevation to calculate an assumed mean annual air temperature. The tree line is indicative of a mean annual ground temperature of 0°C. The calculated air temperature for the tree line elevation , 1800 m.a.s.l., was -2°C. The mean annual air temperature, along with the air freezing are used to obtain the air thawing index. With these values and the surface freezing indices provided in Table 3.5 of Andersland and Ladanyi (1994) the mean annual ground surface temperature was calculated. This result is converted to a mean annual ground surface temperature of -0.3°C. Considering the accuracy of obtaining the tree line elevation from air photos and topographic maps and in obtaining the air freezing index from Figure 15.3 of the Canadian Foundation Engineering Manual (CFEM, 1992), the ground surface is considered to be essentially 0°C and the temperature estimates with elevation are reasonable.

As the Morkill River valley is located on the western slopes of the Canadian Rocky Mountains, there is expected to be a significant effect of elevation on precipitation. In general, moist air masses cool as they are pushed up over the mountains and the water vapour condenses, thus increasing precipitation at upper elevations. In middle latitudes, the general tendency for increased precipitation is modified considerably by leeward or windward slope direction (Barry, 1981). Specifically in the Rocky Mountains, patterns are further complicated by the Pacific origin of water (Barry, 1981). For example, on the western slopes of the Central Colorado Rockies, winter precipitation at 3200 m is almost six times that at the base of the slopes at 1750 m (Barry, 1981).

As detailed precipitation measurements have not been taken in the Morkill River valley, useful generalizations provided in Figure 4.11 of Barry (1981) were used to estimate precipitation in the upper elevations of the Morkill River valley. Compiled data from 1300 long-term weather stations throughout the world was used to derive vertical precipitation profiles for equatorial, tropical, middle latitude and polar regions. Minimum and maximum elevations in the Morkill River valley, 670 m and 2451 m, correspond to approximate annual precipitation totals of 600 and 800 millimetres. In order to compare with known precipitation readings, the estimated precipitation for McBride North (Environment Canada, 1982) at an elevation of 771 m is 600 mm. This is compared to the actual 30-year average of 678 millimetres. The above mentioned charts provide reasonable estimates and are a considered adequate for this study.

Having estimated the climatic conditions in the Morkill River valley, I can now determine the likely form and relative degree of weathering. In 1950, Peltier proposed a system of classifying the degree of weathering, both chemical and physical, that would be based on expected climatic conditions. By utilizing the climatic data from the three chosen weather sites, the Morkill River valley is considered to be susceptible to moderate chemical weathering with weak frost action. The upper elevations that have been interpolated are considered to be susceptible to weak chemical and moderate mechanical weathering.

As a further indicator of the estimates of weathering processes provided by Peltier (1950), an additional weathering classification is considered. Goodman (1993) provides a weathering index comparing precipitation and evaporation rates over the year. The Weinert N value, modified for the Northern Hemisphere, is 12 times the evaporation rate of the hottest month divided by the annual precipitation (Goodman, 1993). Low values of N favor leaching and decomposition (chemical weathering), while high values of N favor disintegration (physical weathering) over decomposition. Methods of estimating evaporation rate are outlined in Blight's 37th Rankine Lecture (Blight, 1997). Based on the limited climatic data for the study region, an estimate of the evaporation rate in the Morkill River valley is from 53 to 70 mm/month. These values would yield Weinert N values of 0.94 to 1.36, which would indicate that the dominant mode of weathering in the valley would be leaching and decomposition.

Station	Elev. (masl)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Mean
McBride	771	-10.2	-4.5	-1.2	4.4	9.3	12.9	15.1	14.1	10.3	5.3	-1.6	-6.4	4.0
North Dome	648	-12.1	-5.5	-2.0	3.4	8.9	12.6	14.7	13.8	9.7	4.3	-2.5	-7.6	3.1
Creek Grande	1250	-12.3	-6.7	-4.9	2.0	7.3	11.0	13.8	13.0	8.7	4.1	-3.9	-7.4	2.1
Cache Calculated	2451	-20.1	-14.6	-11.3	-6.5	-0.8	2.8	5.0	4.0	0.2	-5.4	-11.7	-16.5	-6.1

Table 3.1 Temperature Data (°C) for weather stations near the Morkill River Valley (Environment Canada, 1981a,b)

Station	Elev. (masl)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
McBride	771	72.8	37.0	43.8	44.7	37.8	57.9	51.0	67.1	75.3	72.8	55.6	62.7	678.5
North Dome	648	88.4	66.7	51.1	48.5	46.1	80.7	69.0	91.3	87.2	70.5	58.7	81.6	839.8
Creek Grande	1250	32.4	28.1	40.6	34.5	60.5	96.7	67.1	57.5	46.5	37.4	58.6	42.5	602.4
Cache Calculated	2451													800

Table 3.2 Precipitation Data (in millimetres) for weather stations near the Morkill River Valley (Environment Canada, 1981a,b)

So, considering the climatic data from weather monitoring stations in the region and subjecting climatic data to weathering classifications, the dominant mode of weathering in the Morkill River valley is expected to be chemical with weak to moderate mechanical weathering.

3.5 Preliminary Airphoto Landslide Inventory

3.5.1 Project Description

I conducted a preliminary analysis of landslides in the Morkill River watershed from January to March, 1997. The purpose of the study was to look at the type and distribution of landsliding in the study area.

The reconnaissance air photo inventory of landslides in the Morkill River watershed is based on 1991 air photos provided by the Prince George Forest Region. Portions of the following flight lines are considered in the inventory:

	Photo I.D	Year	Scale
•	30BCB91065	1991	1:20,000
•	30BCB91066	1991	1:20,000
•	30BCB91081	1991	1:20,000
•	30BCB91089	1991	1:20,000

As a study area had not been specified prior to the initiation of the inventory, the area for this study covers the valleys containing the Morkill River, Forgetmenot Creek, Cushing Creek and Hellroaring Creek. The inventory considers any observable landslides located within the height of land to each edge of the creeks or river listed above. An indication of the distrubtion of landslides in the Morkill River valley identified during the landslide inventory is provided in Figure 3.2.

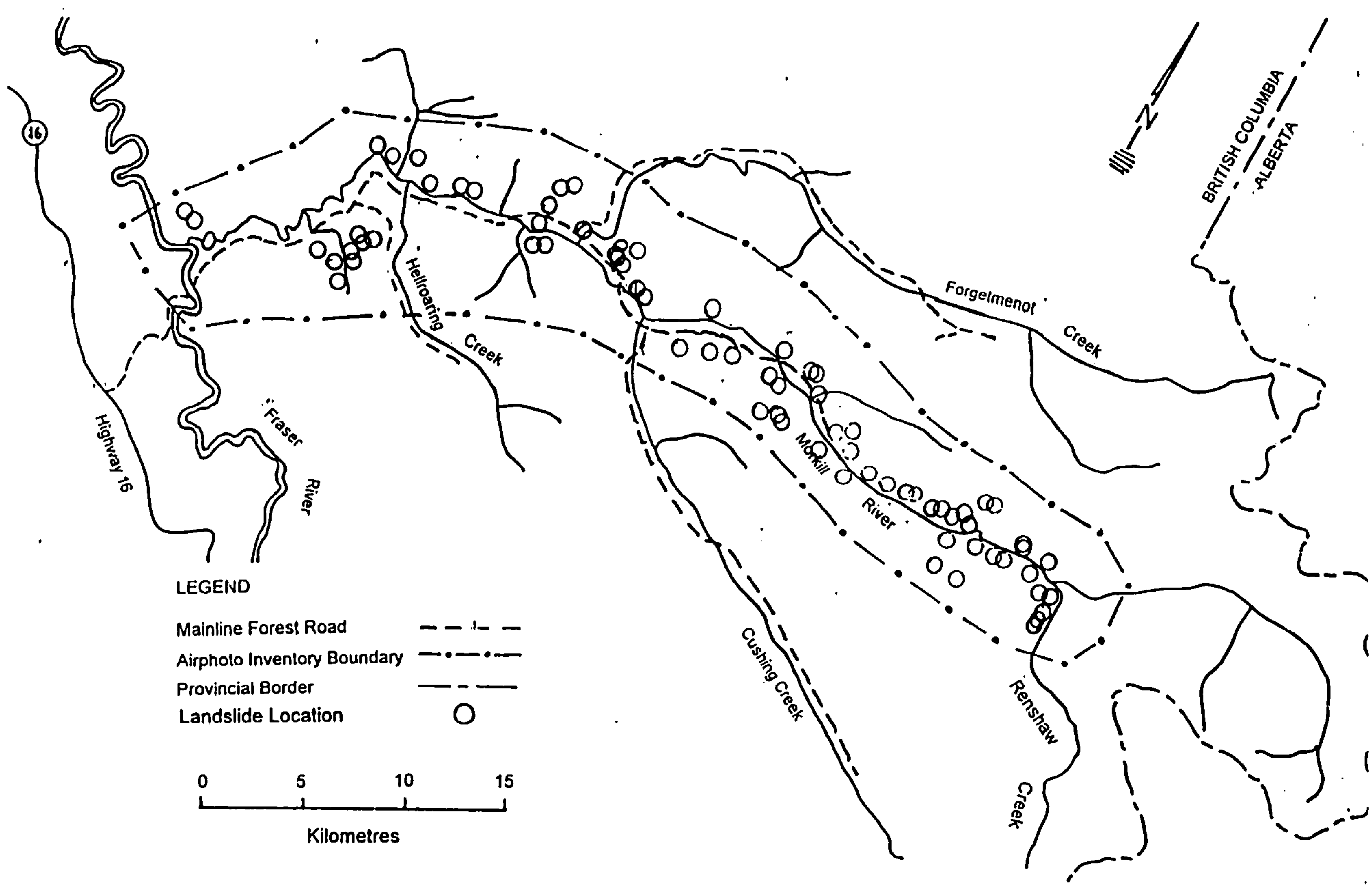


Figure 3.2 Map of Morkill River watershed showing landslide locations inventoried in the Morkill River valley.

As can be appreciated, any landsliding since the summer of 1991 has not been included in this' summary as there is no airphoto coverage provided.

The following sections present the methodology that I used in preparing the attached landslide inventory tables in Appendix A. The airphoto overlays showing each landslide are provided in Appendix B. The sections are presented in the order the topics are covered in the tables and provide a rationale for the descriptions and symbology used throughout.

3.5.2 Landslide Reference System

Landslide Numbering System

The landslide reference system is based on the flight line and photo numbers from the air photos listed above. As all flight lines contained the common prefix 30BCB91, the reference system dropped this prefix and referred to each photo by the last 2 numbers of the flight line number and the 3 digit number representing the particular photo. Using this system, a landslide is then given a number starting at 1 and increasing for each additional landslide shown on the photo.

For example, on photo number 30BCB91065 No. 137, there are 8 landslides, and the eighth landslide is 65137:08.

The landslides and corresponding numbers are shown on the overlays included in appendix B.

Photo Coordinate System

To specify the approximate location of a particular landslide on an air photo, a reference grid system is set up, by first ensuring that the northern edge of the photo is at the top of the photo and, then, setting the origin of a reference grid at the principal point of the photo. The X and Y axes of the grid increased moving to the right and up from this origin in increments of 1 division per 1 cm.

UTM Reference System

The Universai Transverse Mercator (UTM) Coordinates in the inventory tables numbers represent the UTM Coordinates scaled off the 1:50, 000 NTS maps covering the study area. The accuracy of these coordinates is as good as the accuracy of the maps and manual transfer accuracy from the airphotos.

3.5.3 Unit Description

The definitions of the one letter descriptors of the surficial material and surface expression encompassing the landslide areas outlined in the landslide tables in Appendix A, are taken from the BC Terrain Classification System (Howes and Kenk, 1997). These descriptors are outlined below in Table 3.3 and 3.4 respectively.

Symbol	Name	Description
C	Colluvial	Products of mass wastage
L	Lacustrine	Lake sediments; includes littoral deposits
L^G	Glaciolacustrine	Sediments deposited in glacial lakes
M	Morainal	Material deposited directly by glaciers
R	Bedrock	Outcrops/rocks covered by less than 10 cm

Table 3.3 Symbols and Descriptors for surficial materials used in landslide inventory (modified from Howes and Kenk, 1997)

Symbol	Name	Description
a	moderate slopes	Unidirectional surface; 16 to 26 °
b	blanket	A mantle of unconsolidated materials; >1 m thick
h	hummocky	Hillocks and hollow, irregular plan; 15 to 35 °
j	gentle slope	Unidirectional surface; 4 to 15 °
k	moderately steep	Unidirectional surface; 27 to 35 °
m	rolling	Elongate hillocks; parallel in plan; 3 to 15 °
r	ridged	Elongate hillocks; parallel in plan; 15 to 35 °
s	steep	Steep slopes; >35°
u	undulating	Hillocks and hollows; irregular in plan; 0 to 15°
v	veneer	Mantle of unconsolidated material; 10 cm to 1 m thick

Table 3.4. Symbols and descriptors for surface expression (reproduced from Howes and Kenk (1997)).

Aspect

The slope aspect for each landslide has been divided into octants with the following designations: North (N), North-east (NE), East (E), South-east (SE), South (S), South-west (SW), West (W), and North-west (NW).

Drainage

The following designations have been provide for drainage in the area of the landslides:

W: (Well Drained). Well established drainage channels on the slope shedding water quickly away from the slope.

M: (Moderate Drainage). No signs of ponded water on the slope; also no sign of well developed drainage to shed water from the slope.

P: (Poorly Drained). Evidence of ponded water and organic materials located on the slope.

3.5.4 Landslide Description

All landslides that I identified were named based on the scheme outlined in Table 3.2 of Cruden and Varnes (1996). A modified version of the table is presented below in Table 3.5. The names provided on the landslide inventory tables in Appendix A are based on Table 3.5.

ACTIVITY		
STATE	DISTRIBUTION	STYLE
Active	Advancing	Complex
Reactivated	Retrogressive	Composite
Suspended	Widening	Multiple
Dormant	Enlarging	Successive
Abandoned	Confined	Single
Stabilized	Diminishing	
Relict	Moving	
DESCRIPTION OF MOVEMENT		
MATERIAL	TYPE	
Rock	Fall	
Soil	Topple	
Earth	Slide	
Debris	Spread	
	Flow	

Table 3.5 Glossary for forming names of landslides (modified from Cruden and Varnes, 1996)

3.5.5 Landslide Dimensions

In order to quantify the dimensions of each landslide, the length and width of the surface of rupture and the displaced mass are estimated. The length and width estimates given in the attached tables, Appendix A, provide best estimates as to the dimensions of the surface of rupture and displaced mass for each landslide. Please refer to Figure 3.4 of Cruden and Varnes (1996) for a visual diagram of the guidelines used in estimating landslide dimensions from the air photos.

3.5.6 Causes

The numbering system for potential landslide causes is based on the "Checklist of Landslide Causes" of Cruden and Varnes (1996, p.70). Each possible landslide cause is given a number and letter combination which breaks landslide causes into 4 main groupings: geological causes, morphological causes, physical causes and human causes. In order to illustrate the use of the system, a landslide caused by fluvial erosion at the slope toe would be given the designation 2c by Cruden and Varnes (1996). In some cases, where there is thought to be more that one probable cause, the landslide will be given multiple letters. For instance, a landslide that is believed to be caused by a combination of toe erosion and weathering of materials would be given the designation 1c,2c.

3.5.7 Landslide Inventory Summary

Based on the landslide inventory tables presented in Appendix A, the following summary of landslides is provided.

Area	Number of Landslides	Material	
Morkill River	81	Rock (11)	
		Earth (70):	Lacustrine (66)
			Colluvium (4)
Hellroaring Creek	15	Rock (3)	
		Earth (12):	Lacustrine (12)
Forgetmenot Creek	52	Rock (2)	
		Earth (50):	Lacustrine (45)
			Colluvium (5)
Cushing Creek	11	Rock (3)	
		Earth (8):	Lacustrine (8)
TOTAL	159	Rock (19)	
		Earth (140):	Lacustrine (131)
			Colluvium (9)

Table 3.6 Summary of landslides inventoried in the office study

3.6 Conclusions

The Morkill River is located in a valley in the Rocky Mountains that is susceptible to extreme climatic variations. These conditions contribute to a moderate amount of chemical weathering and weak to moderate mechanical weathering of the sediments and bedrock in the area. The weathering of sediments and associated loss of strength appears to be a major contributor to slope instability in the area.

An initial landslide inventory and site visit to the Morkill River watershed highlighted the high susceptibility of the lacustrine sediments in the area to landsliding and erosion. Of the landslides inventoried, 131 of 159 are interpreted to occur in the lake sediments.

Chapter 4: Field Mapping

4.1 Introduction

A field mapping program was initiated in the Morkill River Valley in order to both substantiate the findings of the preliminary office landslide inventory and to map the lateral and vertical extent of the glaciolacustrine sediments in the valley.

Based on field observations as to the extent of sediments and associated landforms, hypotheses as to the glacial history of the area and the origin of the sediments were made.

4.2 Landslide Inventory

Based on the office airphoto landslide inventory, described in Section 3.5, I compiled a list of landslides that required field checks. As the airphotos used for the study were taken in the summer of 1991, further information was required to update the database with any landslides that had occurred from 1991 until the initiation of the field program in May 1997. In order to supplement the above information 1:10,000 airphotos flown in 1995 covering the lower Morkill valley were consulted. The airphotos were prepared by Selkirk Remote Sensing of Richmond, B.C. and the following flight lines were used:

Photo I.D.	Year	Scale
SRS 5453 No. 252-304	1995	1:10,000
SRS 5454 No. 064-109	1995	1:10,000

Based on the results of the preliminary office landslide inventory landslide locations, indicated on the 1:20,000 airphotos and additional sources, I chose sites for field investigation. Access was the main limitation of the field investigation and therefore only 21 landslides that were within 1000 meters of an existing road or cut block were visited. Due to budgetary restrictions, helicopter time was not made available and therefore some remote sites, including all sites beyond the eastern extent of the Morkill River Forest Service Road (FSR), were not visited during the field investigation.

The field program took place from the middle of May 1997 to middle of August 1997. The time spent was organized to start the investigation on the large scale and to focus more as the investigation progressed. In order to ensure the most efficient use of time in the field, I began the investigation at the mouth of the Morkill River at the Fraser River and progressed in an easterly direction up the Morkill Forest Service Road (FSR) and the tributary roads that branched off the main road.

For each site chosen, access was made by road to the closest possible location, as deemed by the airphotos and 1:20,000 Terrain Resource Inventory Mapping (TRIM) maps. For locations where vehicle access was not available, access was made by foot using airphotos, maps and compass to navigate.

Once each landslide was located I made the following observations: landslide type, elevation, aspect, land-use, hillslope configuration, slope position, soil type and properties, and slope angle and dimension measurements.

Observations of the dimensions of each landslide were made using a 50 m cloth tape. Measurements of total length included estimates of the relative proportions of rupture surface and displaced mass. For slides located adjacent to rivers and creeks, I assumed that the displaced mass had been eroded and therefore the rupture surface composed the entire length of the landslide. The observations of width were taken at a location judged in the field to be representative of an average width of the landslide. Width observations were taken for both the rupture surface and displaced mass in most cases.

I took measurements of natural slope angles and slope angles of the landslides using a hand held clinometer. This device requires the user to sight up or down to a location to which a relative inclination is required. Once the object has been sighted, a leveling bubble apparatus attached to a gradational inclination scale is manipulated to a point where the apparatus is level, thus providing the relative inclination on the attached scale. All slope angle measurements were recorded on field data cards and these data have been presented as Appendix A.

Observations of soil type were made at each landslide location and stratigraphy gathered. I visually classified soils according to the Unified Soils Classification System (Casagrande, 1948). The carbonate content of the soil was classified by applying a 0.1 M solution to the soils and recording the observed reaction. The scale used was a relative classification based on observations of the effervescence of the soil (Agriculture Canada, 1974). The reaction was classified in a range from non-effervescent to highly effervescent, from a soil that did not react with applied HCl to one that reacted violently. Observations were recorded on British Columbia Ministry of Forests (BCMOF) Field Landslide Inventory cards and a summary of the observations is recorded in Appendix A.

In the field investigation 21 landslides were visited and described. The results of this inventory are provided in the Appendix A and are further discussed in Chapter 7.

4.3 Ground Proofing Airphotos

During the initial landslide inventory, I made inferences as to the composition of the surficial soils based on available 1:20,000 airphotos. Once in the field, the proposed soil classifications required field verification to begin to ascertain the lateral and vertical extent of the lake sediments in the valley.

In order to supplement the information gathered during the landslide inventory, I initiated a systematic data collection program to compile soils observations of accessible river exposures and road cuts in the study area. Access to and along the roads in the study area was made by a combination of truck, all terrain vehicle (atv) and by foot. In order to be systematic and thorough, the ground proofing began at the easternmost accessible portion of the Morkill River valley and proceeded downstream to its confluence with the Fraser River. At each location to be described, the exposure was located on a 1:20,000 topographic map, referenced and described. Once back in the office, the visual soil observations were transferred to hand drawn lateral and longitudinal cross-sections of the valley. Cross sections showing the distribution and type of sediments in the Upper and Lower Morkill River valley, as well as the confluence with Forgetmenot Creek are shown in Figures 4.4 through 4.6.

4.4 Bedrock Geology (Stratigraphy)

The Morkill River study area occurs within the Park Ranges of the Rocky Mountain Physiographic Region as identified by Holland (1964, Figure 2). The area is characterized by folded and faulted sedimentary, and to a lesser extent, metamorphic rocks, consisting of sub-parallel ridges and valleys which predominantly trend northwestwards (Holland, 1964). More precisely, the area encompassing the Morkill River and tributary valleys was identified as the Forgetmenot Zone by Campbell et al. (1973, Figure 4.4); this zone identifies the structural geology of the area dominated by fine-grained rock with inclusions of medium and coarse grained rock.

This section provides a discussion of the local bedrock geology of the Morkill River study area. It is taken from previously published work by Campbell et al. (1973) , Mountjoy (1980) and Carey and Simony (1984). It should be noted that the above mentioned studies were completed prior to the pioneering of the forestry road in the upper Morkill River valley and did not have the luxury of the road cut exposures that I explored during the field investigation. For discussion purposes, the study area will be described by geological grouping in a chronological order from oldest to youngest. The stratigraphic column presented in Figure 4.1, should be consulted in conjunction with this section.

The three units of the Miette Group are lithologically distinct in the Morkill River area. The lower Miette Group consists of folded and cleaved black shale, argillite and limestone units (Campbell et al, 1973). The limestone unit consists of calcareous, coarse grained sandstone to granule grit; finely crystalline black limestone and silty black slate (Carey and Simony, 1984). Based on the mapping by Campbell et al (1973) the lower Miette group is confined mainly to the Cushing Creek valley. In a study of the Cushing Creek area, Carey and Simony (1984) reported an estimated thickness of 380 metres as a minimum for the lower Miette. During my field investigation I noted the existence of a black limestone quarry at 35.5 km on the Morkill FSR which is similar to the description above.

The Middle Miette is the dominant unit in the Morkill River valley, underlying the majority of the Morkill River, Forgetmenot Creek, and Cushing Creek. The middle Miette Group comprises interlayered cliff-forming stacked grit and sandstone beds (units up to 385 metres thick), recessive, rusty weathering, silty, dark green to medium grey slate units (up to 210 metres thick) and minor medium grey limestone (Carey and Simony, 1984). Pebble conglomerate is also found associated with the sandstone at most locations including the roadside quarry at Kilometre 44 on the Morkill River FSR. The measured thickness of the middle Miette is 2870 metres (Carey and Simony, 1984).

The upper Miette Group consists of predominantly grey to dark grey mudstone and silty argillite, generally cleaved and folded, and includes a variably thick zone of coarse clastic rocks (Campbell et al, 1973). The upper Miette Group occurs in the study area as a thick band being cut at a right angle by the Morkill River, upstream of Hellroaring Creek, and along the top of Forgetmenot Mountain, trending down towards, and along the Upper Morkill River. Thickness for the upper Miette in the vicinity of the study area is estimated at approximately 1800 metres (Carey and Simony, 1984).

The McNaughton Formation outcrops in roadcuts in the lower Morkill River valley and is dominated by white quartzite that abruptly overlies the argillaceous, fine grained sandstones and siltstones of the upper Miette (Carey and Simony, 1984). Campbell et al, (1973) described divided this formation into three lithofacies: a basal conglomerate, feldspathic sandstone; quartzose sandstone and an interbedded sandstone-shale facies. Reported thickness of the McNaughton Formation is 1370 metres (Campbell et al, 1973).

The Gog Group is a sequence dominated by quartzite which overlies the Miette Group in the southern Rocky Mountains (Campbell et al, 1973). The rocks of this group are Lower Cambrian in age and have been subdivided into the quartzose sandstone of the Mahto Formation and the carbonate rocks of the Mural Formation. Outcrops of the Mural and Mahto Formations are rare but, according to Campbell et al (1973) , they are located along the south-west ridge of Hellroaring Creek, a tributary to the Morkill River. Reported thickness of the Gog Group range from 1370 metres to 2290 metres (Campbell et al, 1973).

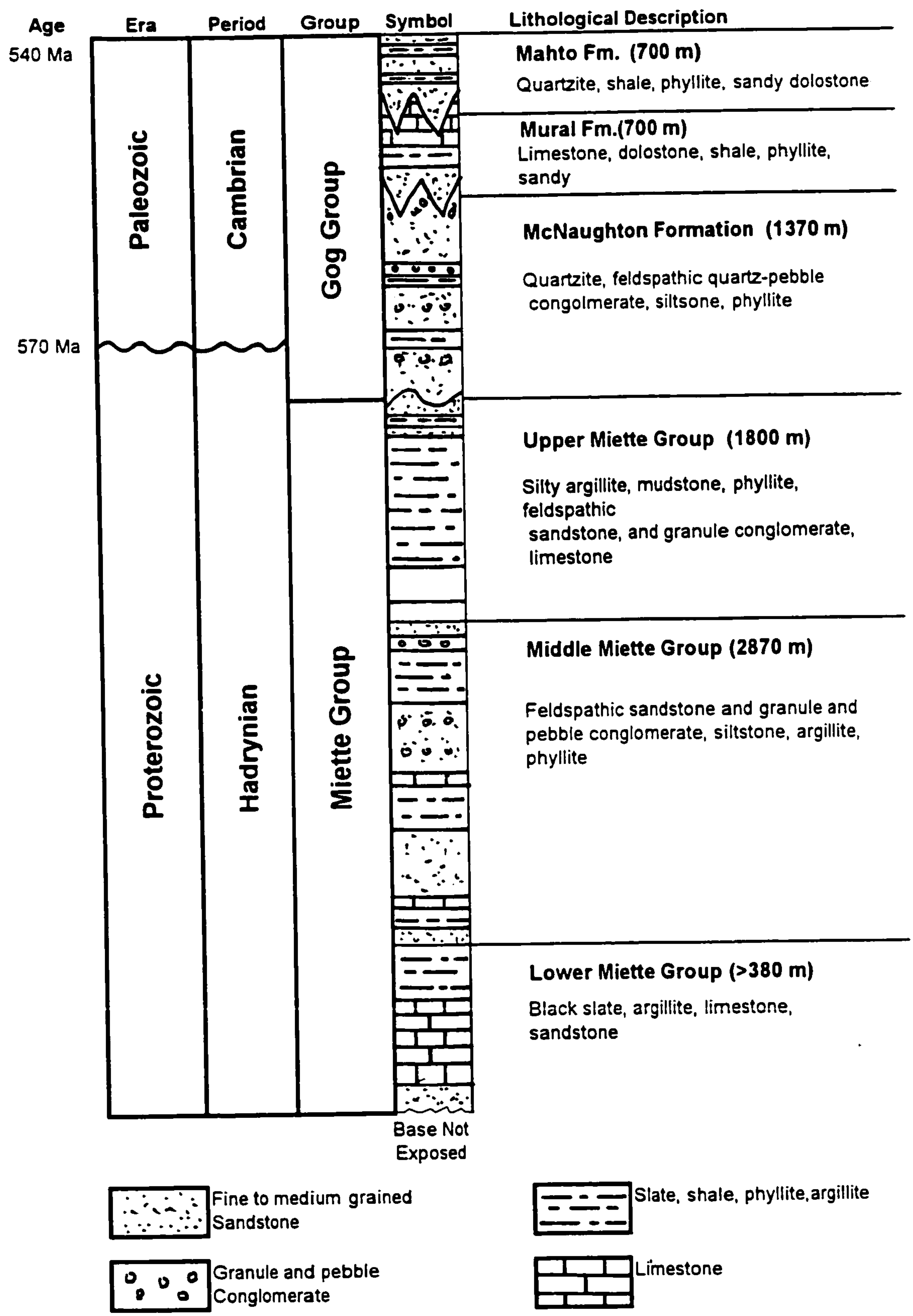


Figure 4.1 Stratigraphic column for the Morkill River area

4.5 *Surficial Geology*

4.5.1 Glacial History

As with most of British Columbia, the Morkill River study area was enveloped by the Cordilleran Ice sheet during the Pleistocene (Clague, 1989). For the study area, the most important period of glaciation was the late Wisconsinan glaciation known as the Fraser Glaciation, which occurred between 29,000 to 14,000 years before present (Ryder et al, 1991).

During the Fraser Glaciation the entire study area was glaciated by a series of local valley glaciers. Many of the features found within the study area today (hanging valleys and cirques for instance) are the result of these valley glaciers. In mountain regions, the cycle of glaciation is considered to begin with the formation of small cirque glaciers which, by continued growth, expanded into mountain and valley glaciers (Holland, 1976). These small glaciers advanced downwards, along topographic lows and coalesced into large valley glaciers, and subsequently formed larger ice sheets.

As described by Tipper (1971), north-easterly moving ice from the Coastal Mountains met south-westerly moving Cariboo Mountain ice resulting in a deflection of ice flow both to the southeast and northwest towards the Rocky Mountains. Clague (1989) hypothesized that the Fraser Ice Sheet overwhelmed the valley glaciers, covering the ranges with so much ice that only the higher peaks stuck above it as nunataks.

Approximately 12,000 years before present, a distinct climatic warming caused a slow meltdown of the glaciers. Fulton (1967) studied deglaciation in areas of moderate relief and contended that it was accomplished by down wasting, stagnation along valleys and eventual decay in separate blocks of ice. Upland regions melted first, dividing the coalesced ice sheets into a series of valley tongues that retreated in response to local conditions. Applying this hypothesis to the Morkill River valley, would suggest that the tributary valleys, in which the ice sheets were of lesser thickness than the main valley glacier began to downwaste and stagnate first. These were followed by the Morkill River valley ice sheet itself, with the final sheet to stagnate being the main Fraser River valley ice sheet.

During calmer periods (low energy environments), water was trapped in kettles (depressionai topography), or low lying areas (valley bottoms) behind dams caused either by remnant ice or mass wasting, blocking the free flow of the water. Moreover, it is also possible that lakes were built up on the ice surface. The resulting glaciolacustrine sediments, a mixture of silt and fine sands, are found extensively throughout the Morkill River and Forgetmenot Creek valleys and to a lesser extent, within the valleys of Hellroaring and Cushing Creeks. While these deposits are extensive and probably the most recognizable landform within the study area, they are not continuous (due to subsequent erosion and landsliding) and occur at different elevations throughout the entire study area. As can be seen in the attached longitudinal profile, Figure 4.2, glaciolacustrine sediments can be found as high as 450 metres above the present river and stream courses.

After the final recession of the glaciers, during Holocene time, colluvial and fluvial processes were active in sedimentation and landscape forming. The impact of these processes on what the surface is composed of and how the landscape looks today has been quite strong, as there are no well expressed glaciomorphological feature visible anymore (Ryder and Clague, 1989). Hypotheses as to the deglaciation and corresponding deposition of sediments in the Morkill River valley are discussed in Section 4.6.

4.5.2 Surficial Materials

Till: Lodgment till and/or ablation (melt-out) till derived from glacial processes is commonly found on mid to lower slope positions within the study area. Till, in general, contains particle sizes ranging from very large boulders to clay-sized particles. The type of lodgment till found within the Morkill River study area occurs as a non-stratified mixture consisting of a fine grained matrix of silt and clay with angular clasts of limestone, quartzite and siltstone comprising the coarse fraction.

Ablation till which may sometimes be slightly stratified, generally contains a greater amount of sand and larger, angular boulders derived from the bedrock of the Miette and Gog groups. Evidence of lodgment till was found on the mid to upper slopes throughout the Morkill River and tributary valleys. Ablation deposits were noted to the west of the confluence of Forgetmenot Creek and Morkill River.

Lacustrine : The glaciolacustrine sediments are the most widespread surficial material. Properties of the lake sediments taken from the various sections in the valley are discussed in Chapter 6. Vertical distribution of the lake sediments is shown in Figure 4.2 and discussed in Section 4.6.

Generally, the glaciolacustrine material consist of rhythmic sequences of silt, fine sand and clay sized material. The landforms associated with the glaciolacustrine deposition have been highly altered as a result of post glacial erosion, landsliding and human activity. Typical landforms associated with glaciolacustrine deposition in the Morkill River valley consist of irregular terrace features, linear steep-sided ridges, long sinuous ridges and gullied terrain.

Based on the bedrock geology and the violent reaction of the lake sediments with hydrochloric acid, it is considered that a large portion of the lacustrine sediments in the valley is cemented by calcite, possibly either derived directly from the limestone of the Lower Miette Formation or from calcite-rich lodgment till. Subsurface springs running along faults and originating from subsurface carbonates are also a possible source of calcite. These hypotheses are considered in Chapter 7.

Colluvium: Colluvium is often noted in isolated patches in the lower elevations of the Morkill River valley, but predominantly occurs on the upper to middle slopes and mountain peaks.

On the upper slopes, colluvial materials are predominantly coarse and bouldery and derived from adjacent bedrock outcrops on mountain peaks. On the middle to lower slopes, the colluvium consists of a diamicton, comprised of both fine grained silt and sand sized particles to large, angular boulders. These materials are usually found as thin veneers (less than 2 metres thick) and in fan shaped deposits.

4.6 Establishment of Lake Levels

Based on the information on stratigraphy gathered during the field investigation, I hypothesize that there are a minimum of six levels of lake sediments in the Morkill River valley. The discussion of these different levels will begin at the mouth of the Morkill River and continue upstream, to the north-east. The longitudinal profile of the Morkill River, Figure 4.2, should be consulted in conjunction with following section. The symbols shown as drainage divides represent the elevations of the heads of the tributary creeks at the boundary of the Morkill River watershed.

LAKE A

Beginning at the confluence of the Morkill and Fraser Rivers, a level of lake sediments is considered to exist with a top elevation at 840 m.a.s.l. My stratigraphic logging, supplemented by test pit and borehole information gathered in an investigation by the BC Ministry of Transportation and Highways (BCMOTH, 1996), indicates that the lowest lake level consists of a varved sequence of sand, silt, and clay. This lowest lake level is considered to correspond with the level of lake sediments in the Rocky Mountain Trench in this vicinity of McBride and is characterized by a broad, level bench that overlooks the confluence of the Morkill and Fraser rivers. This level, 840 m.a.s.l. is approximately 80 metres above the maximum elevation of Glacial Lake Prince George as reported by Tipper (1971).

LAKE B

To the east of the confluence of Hellroaring Creek and the Morkill River, lake sediments of predominantly silt size are evident to a maximum elevation of 900 m.a.s.l. It is hypothesized that this sediment was deposited up against the main Fraser Valley ice sheet during deglaciation, as the main Morkill River valley glacier was in final stages of decay. The easternmost extent of this deposit is characterized by the flat bench area in the vicinity of the mouth of Cushing Creek.

LAKE C

Progressing eastward, up the Morkill River valley, the next level of lake sediments is considered to have a maximum elevation of 1020 m.a.s.l. Stratigraphic logging undertaken during the field investigation indicated that this level of lake sediments consists of predominantly poorly graded sand with interbeds of well graded sand and silt. This lake level was deduced due to the presence of a relatively continuous level of sediments with similar soil properties located throughout the valley. The easternmost extent of this deposit was noted to the west of Wolf Creek and continued westward to the Hellroaring Creek.

LAKE D

To the east of the confluence of the Hellroaring Creek and the Morkill River, a lake level consisting of predominantly silt size material is evidenced to a maximum elevation of 1120 m.a.s.l. This level was found continuously from the Hellroaring Creek confluence, eastward to the most easterly extent of the accessible area in the upper Morkill River Valley. I hypothesize that a large block of stagnant ice at the present confluence of Hellroaring Creek and the Morkill River impounded a large lake, encompassing the upper Morkill River, Cushing Creek and Forgetmenot Creek. As the area was flooded, sediments derived from the bedrock of the Gog Group, McNaughton Formation and the Upper, Middle and Lower Miette Formations were deposited. This level is characterized by plateaus dissected by postglacial streams to form long sinuous ridges cresting at 1120 metres.

LAKE E

Based on the limited access to the Upper Morkill River valley and the airphoto reconnaissance, an uppermost lake level with a maximum elevation of 1260 m.a.s.l. was noted. This unit extents longitudinally eastward from the area of the confluence of Forgetmenot Creek and the Morkill River, to the Upper Morkill River valley in the vicinity of Renshaw Creek. The easternmost extent has been assumed based on available air photos and topographic data.

This level of lake sediments is hypothesized to have been dammed at the confluence of the Forgetmenot Creek and Morkill River. Sediments at the 1260 level were noted on both sides of Cushing Creek and along the Morkill River, east of this point. Along the Morkill River valley to the west of the confluence, no sediments of this level were noted.

In the Upper Morkill River valley, characteristic sinuous, finger-like remnants of these sediments were noted on the airphotos. The upper tips of the remnant ridges extended to a common elevation of approximately 1250 metres, based on available topographic mapping of the area.

LAKE F

Near the eastern extremity of the study area, in the vicinity of Wolf Creek, evidence of a smaller lake was encountered at a maximum elevation of 1000 m.a.s.l. The sediments of this lake were finer grained than those evident throughout the majority of the study area and were visually classified as a silty clay. I hypothesize that this lake was formed in a still water, back pond blocked at some point by a large mass of stagnant ice, a large landslide or a large alluvial fan which has since been eroded. Both the airphoto study of the area, as well as evidence of a large fan deposit, indicate that a narrow section of the Morkill River valley was blocked for some time in the final stages of deglaciation or in postglacial times. Based on the topographic maps, as well as the published bedrock geology, it appears that this lake was fed by Wolf Creek, with the sediments derived from the phyllites and mudstone of the McNaughton Formation that encompasses the Wolf Creek basin.

This hypothesis would account for the isolated nature of the fine grained sediments in relation to the majority of the sediments encountered in the valley.

OTHER LAKE LEVELS

GEOWEST Environmental Consultants (Geowest, 1994) reported that lake levels were encountered at much higher elevations in the adjacent Forgetmenot Creek valley. Geowest (1994) reported that the uppermost, and supposedly oldest, deposits were found on the south face of Forgetmenot Creek at an elevation of about 1,620 m.a.s.l. Geowest(1994) also indicated two subsequent levels of lake deposits in the Forgetmenot River valley: a secondary stage at approximately 1500 m.a.s.l. and the lowest stage in the Forgetmenot River near its confluence with the Morkill River. The maximum elevation of this lower lake level was found to be at approximately 1340 m.a.s.l. during my field investigation.

4.7 Conclusions

By following through the landslide inventory and subsequent surficial mapping, observations as to the properties and distribution of the sediments and parent materials in the Morkill River valley were made.

It was concluded that at least six lake levels are present in the Morkill River valley as a result of complex stagnation and downwasting of valley glaciers during late glacial and early Holocene time. At various times, it is hypothesized, large blocks of ice and debris formed natural dams throughout the Morkill River valley and tributary valleys, producing a variety of large sediment traps . The sediments in these lakes were generated from the local bedrock in the Morkill and tributary valleys, with weakly cemented sediments in the valley most likely derived from the rocks of the Lower Miette Group.

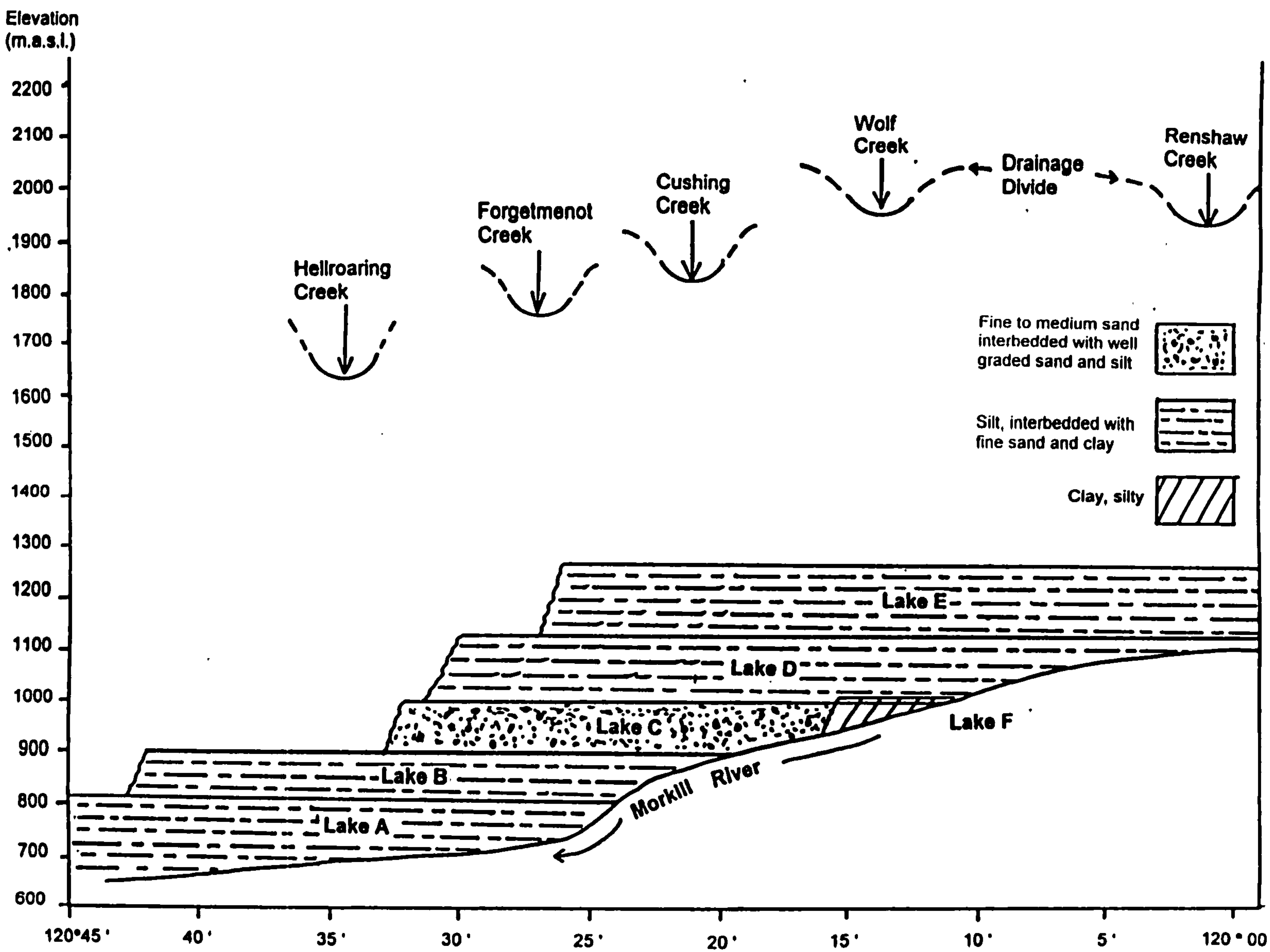


Figure 4.2 Levels of lake sediments in the Morkill River valley. Locations of tributary valleys shown on Figure 5.1.

Chapter 5: In situ Field Testing

5.1 Introduction

During the preliminary field mapping program, discussed in Chapter 4, I noted an observable gain in strength and increase in density with depth in exposures in natural and artificial exposures in the Morkill River valley. Based on the relative steepness of the slopes and density of sediments, it was hypothesized that the soils were cemented. The bedrock geology and assumed sedimentary environment of the area led to the belief that the most likely cementing agent was calcite, derived from the Lower Miette Group or Paleozoic carbonates possibly eroded by ice which flowed into the area.

The purpose of the field testing program was then to document the relative change of in situ density and carbonate content at exposures. This data can quantify the relative amount of weathering by looking at the change in density and potential removal of carbonates by surficial processes.

In order to quantify changes in density with increasing depth in exposures, I took density profiles at ten sites throughout the Morkill River valley. The density profiles were obtained using a rubber balloon apparatus (ASTM, 1997b).

As an indicator of the percentage of carbonates occurring in the lacustrine sediments, the relative effervescence of the soil was described. The relative effervescence is estimate by standards used by soil scientists in the classification of free carbonates in soils (Agriculture Canada, 1974).

5.2 Density Testing

In situ density testing was required in order to quantify the change in density with depth of the soils in the Morkill River valley. The method chosen to obtain the field density observations, the rubber balloon method (ASTM, 1997b) was chosen for this study for three main reasons. Firstly, the apparatus was durable, which was important as access to some sites was rough. The apparatus weighed approximately four kilograms, was under one metre in length, and can be transported by ATV or in a back pack. Second, the rubber balloon displacement method is considered to provide reliable and repeatable results (ASTM, 1997b). The third advantage of using the rubber balloon method is that the sample to be returned to the laboratory for moisture content analysis allows further soil classification, index testing and carbonate determination on samples taken from the exact location at which the density readings were taken.

Ten sites were chosen during the field mapping program for density testing. Sites were chosen both to be accessible, as equipment and samples had to be transported, and to be representative of the variability across the study area. The approximate test locations are shown on Figure 5.1.

Figures 5.2a-j. provide a visual indication of the variation of density with depth. As can be seen from the profiles, bulk densities ranging from 1.4 to 2.0 Mg/m^3 were measured in the lacustrine sediments in the Morkill River valley. The corresponding range of dry densities is 1.37 to 1.75 Mg/m^3. A density increase is noted in most profiles at depths ranging from 0.3 to 0.6 m below the ground surface. Data trends and their correlation with carbonate content are discussed in relation to the slope processes in Chapter 7.

An indication of the relative accuracy of the field density values, when compared to the values obtained from samples measured in the laboratory, is presented in Section 6.4.

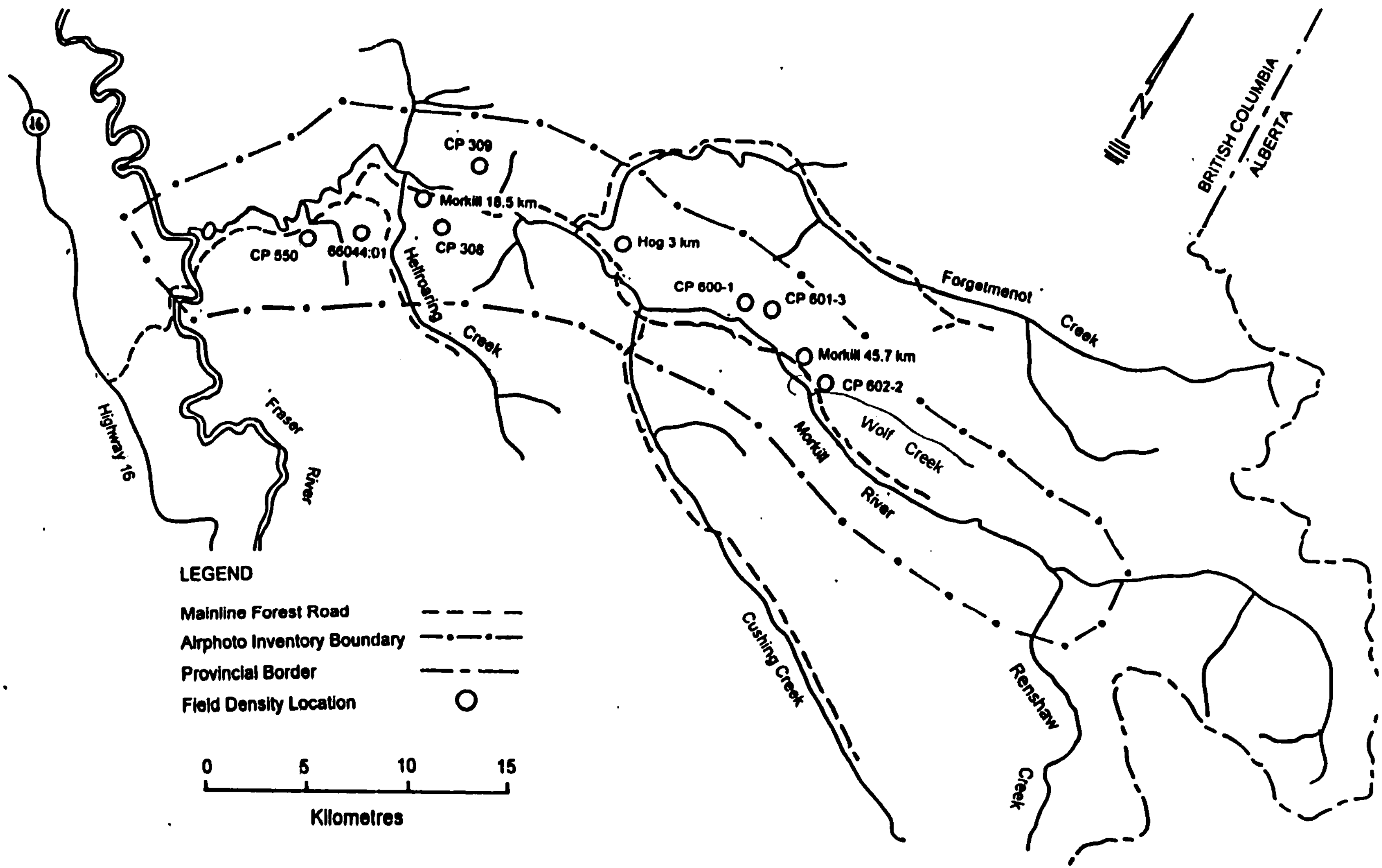
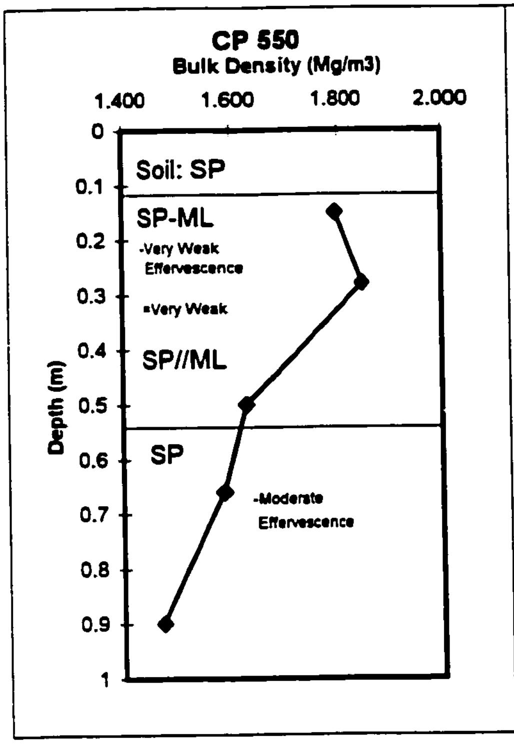
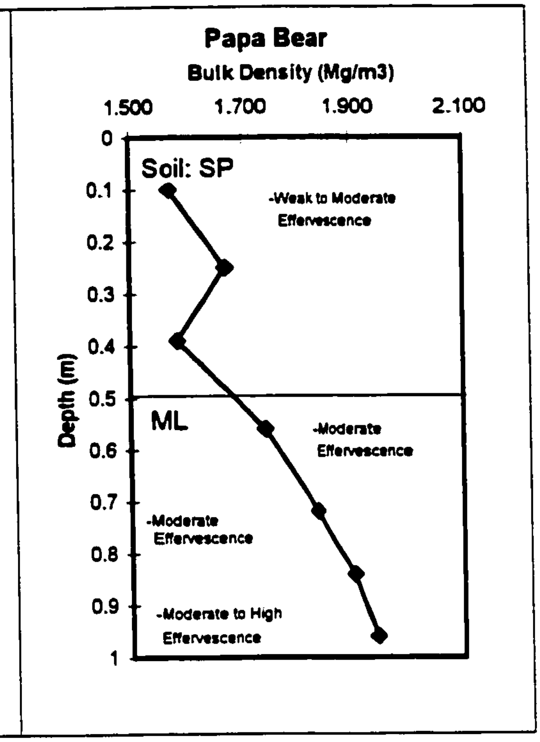


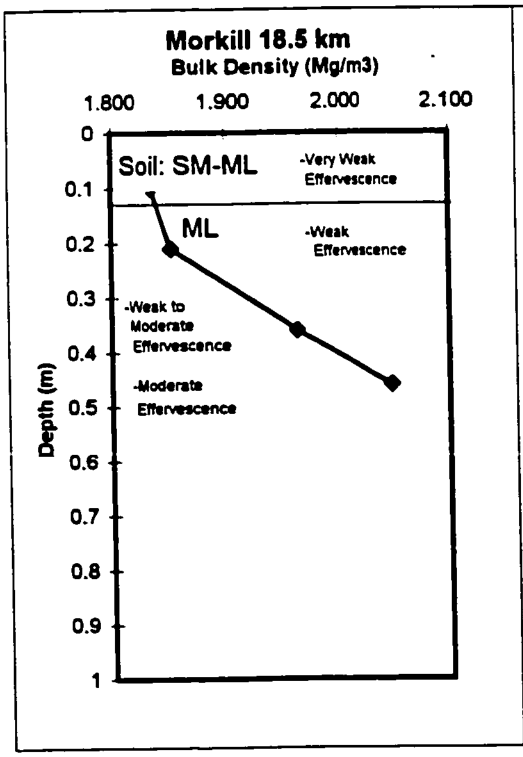
Figure 5.1 Map of Morkill River watershed showing field density profile locations



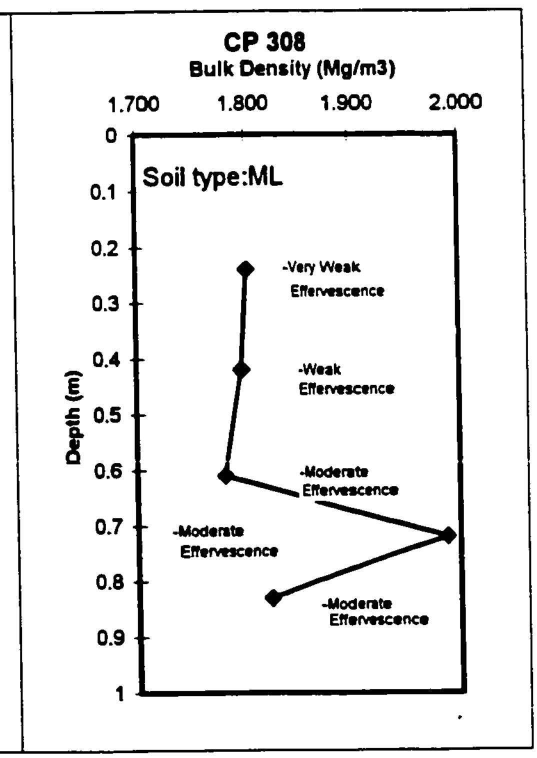
a). Profile 550-1



b). Profile 66044:01

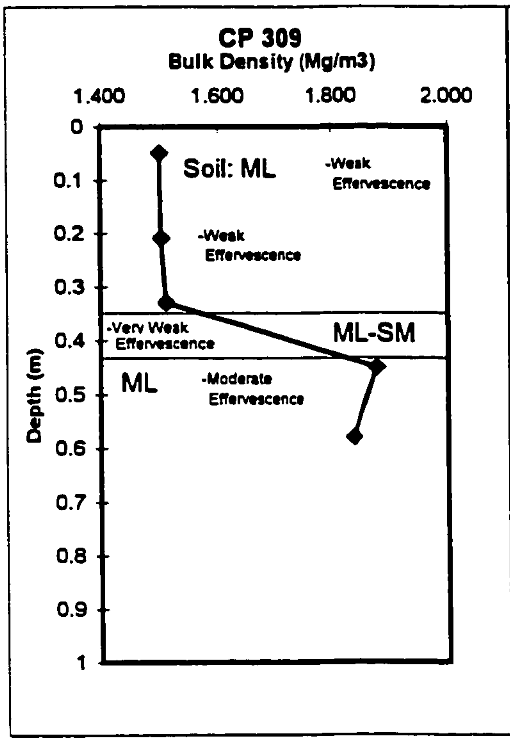


c). Profile Morkill 18.5 km

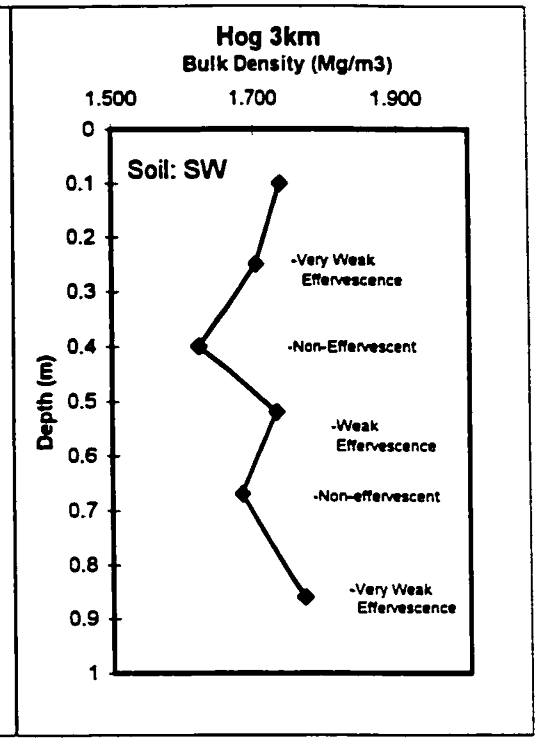


d). Profile CP 308

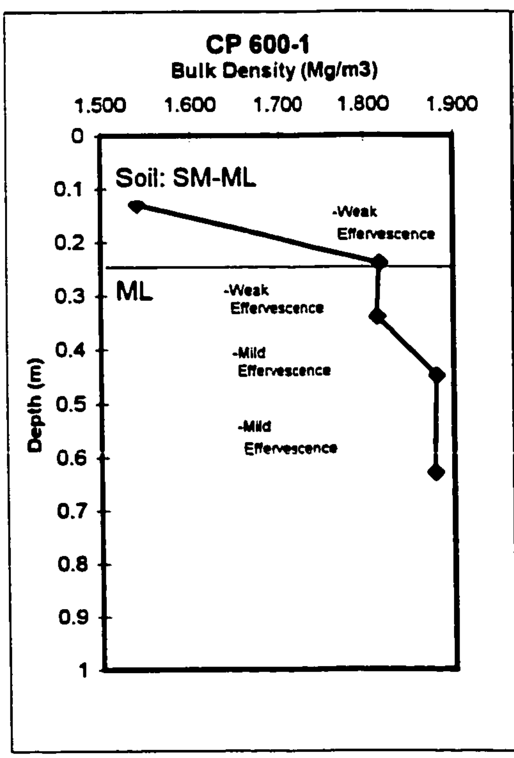
Figure 5.2.a-d. Field density profiles for locations in the Morkill River Valley



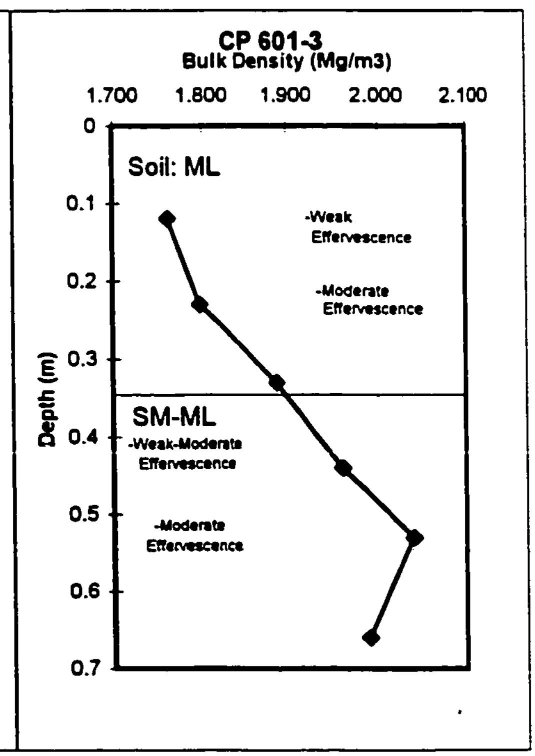
e) Profile CP 309



f) Profile Hog 3 km

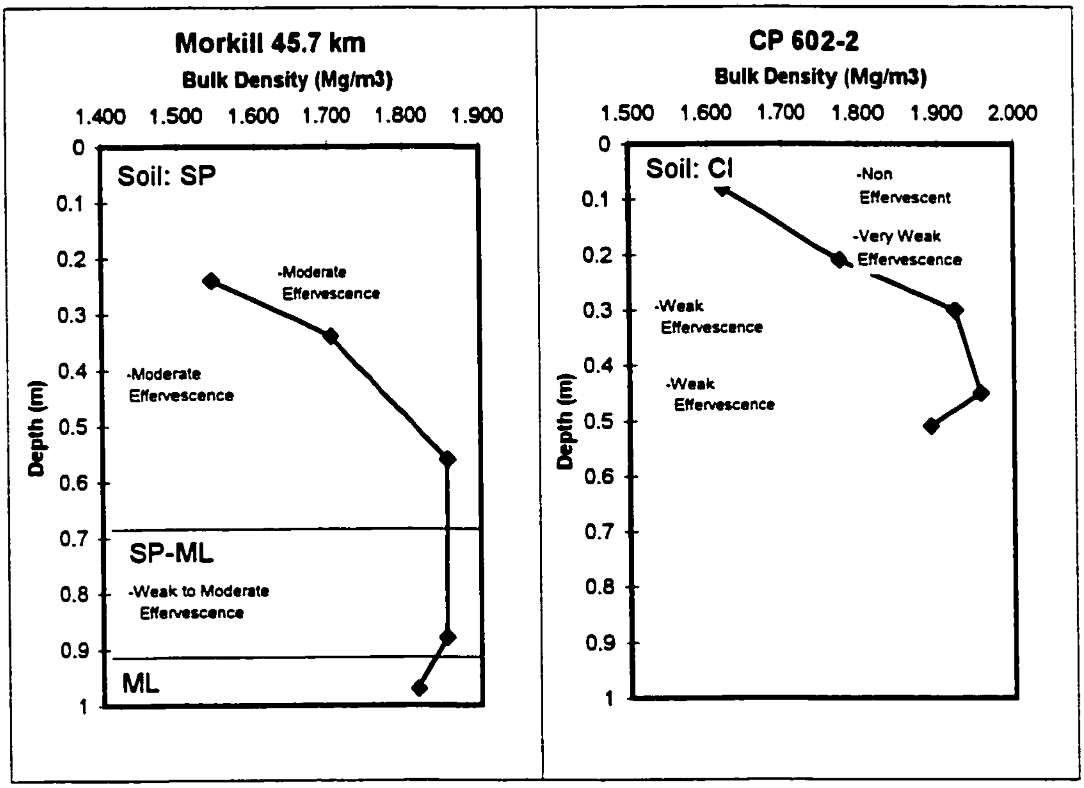


g) Profile CP 600-1



h) Profile CP 601-3

Figure 5.2.e-h. Field density profiles for locations in the Morkill River valley



i) Profile Morkill 45.7 km

j) Profile CP 602-2

Figure 5.2.i-j. Field density profiles for locations in the Morkill River valley

5.3 Carbonate Determination

To assess the relative amount of cementation and the distribution of carbonate sediments across the study area the soil was subjected to a solution of 0.1 M Hydrochloric Acid (HCl). A system, which visually estimates the reaction with HCl , the effervescence, is a standard test from the System of Soil Classification for Canada (Agriculture Canada, 1974) and is as follows:

very weakly effervescent	-	a few bubbles
weakly effervescent	-	bubbles readily observed
moderately effervescent	-	bubbles form a low foam
strongly effervescent	-	bubbles form a thick foam

The qualitative criteria are also divided into calcareous grades as follows (Agriculture Canada, 1974):

weakly calcareous	1-5%	as $CaC0_3$ equivalent
moderately calcareous	6-15%	as $CaC0_3$ equivalent
strongly calcareous	16-25%	as $CaC0_3$ equivalent
very strongly calcareous	26-40%	as $CaC0_3$ equivalent
extremely calcareous	>40%	as $CaC0_3$ equivalent

Based on the above qualitative criteria, the soils in the Morkill River valley were described predominantly as very weakly to moderately effervescent. This further corresponds to a calcareous grade of weak to moderate, 1-15% calcium carbonate equivalent. Indications of the qualitative field observations of carbonate contents of the soils in the Morkill River valley are presented in the density profiles in Figures 5.2.a-j. as well as on the field landslide forms presented in Appendix A.

5.4 Conclusions

The main purpose of the in situ testing field program was to quantify relative change in density with depth of the lacustrine sediments and also the corresponding change in carbonate content. The field estimation of carbonate content provides a relative scale during the field program that would be backed up quantitatively using samples taken from the density testing program. The soils in the Morkill River valley were classified as weakly to moderately calcareous based on the criteria outlined. The in situ density tests yielded densities in the undisturbed sediments of up to 2.05 Mg/m^3.

Based on the field observations there appears to be a relationship between the in situ densities and observed carbonate content. As weathering is less effective with increasing depth, there is an increase in calcium carbonate and a corresponding increase in density. This density increase also correlates to an increase in strength of the soils. This relation was quantified in the laboratory program, as discussed in Chapter 6.

Chapter 6: Laboratory Testing

6.1 Introduction

The main hypothesis of this study was that the dissolution of calcium carbonate and disaggregation of the soil matrix due to frost action contributed to the overall breakdown and loss of strength of the cemented lacustrine sediments. Therefore, the aim of the laboratory program was to quantify the geotechnical properties of both the weathered and unaltered lake sediments.

As this is considered to be a reconnaissance study of these type of soils, laboratory tests were predominantly index level tests used to gather the basic characteristics of the soils in the Morkill River valley.

Plasticity and grain size testing were undertaken to assess the index properties of the soil in order to supplement the field soil classification.

Density tests were undertaken on field samples taken in the form of Shelby Tube samples or block samples. Samples were trimmed, measured, weighed and dried in order to determine the moisture and density characteristics of the in situ material. I then compare these results, along with their corresponding void ratios, with those obtained in the field using the rubber balloon method (ASTM D2167-94) and discuss the results.

The mechanical weathering mechanisms are assessed by addressing the frost susceptibility of the lacustrine materials in the Morkill River valley. Classifications for frost susceptibility based on the Atterberg Limits and grain size analyses are presented. As well, a more recent correlation of the plasticity of the fines fraction and the clay fraction with segregation potential is considered.

In order to quantify the frost susceptibility of the lacustrine sediments, the thaw weakening effects are considered by subjecting samples from two sites to 10 cycles of freeze and thaw. Once samples were subjected to a set number of cycles of one-dimensional freeze and thaw, they were tested in an Unconfined Compression test apparatus to assess the relative loss in strength.

To quantify the carbonates in the soil matrix, a vacuum distillation/titration method was utilized. This method measured the amount of carbon dioxide (CO_2) gas emitted upon subjecting soil samples to a 2.0 M HCl solution. Measurements were made by titrating a base solution of known concentration with the absorbed CO_2 to determine the amount of CO_2 emitted during the reaction with HCl. The precision of this test procedure is reported to be +/- $3*10^{-4}$ (Bundy and Bremner, 1972).

Scanning electron microscopy gave a picture of the structure of the soils and the form of carbonates present in the soil matrix. Electron diffraction was also utilized to gather information as to the elements consitituting specific grains in the soil matrix.

6.2 *Grain Size Analysis*

The gradational properties of the lacustrine soil of the Morkill River valley are essential to compare and contrast the types of sediments and their distribution. Samples were prepared as per ASTM D422-63 and the grain size distribution obtained using hydrometer analyses (ASTM, 1997d). The results of the tests are shown graphically in Figure 6.1.

As evident from Figure 6.1 the lacustrine sediments in the Morkill River valley are predominantly silt size. With the exception of the samples taken at the Hog Road, Morkill 45.7 km and CP 550-1, the silt fraction of the sediments ranges from 51 to 95% with corresponding clay fractions ranging from 43 to 5 %.

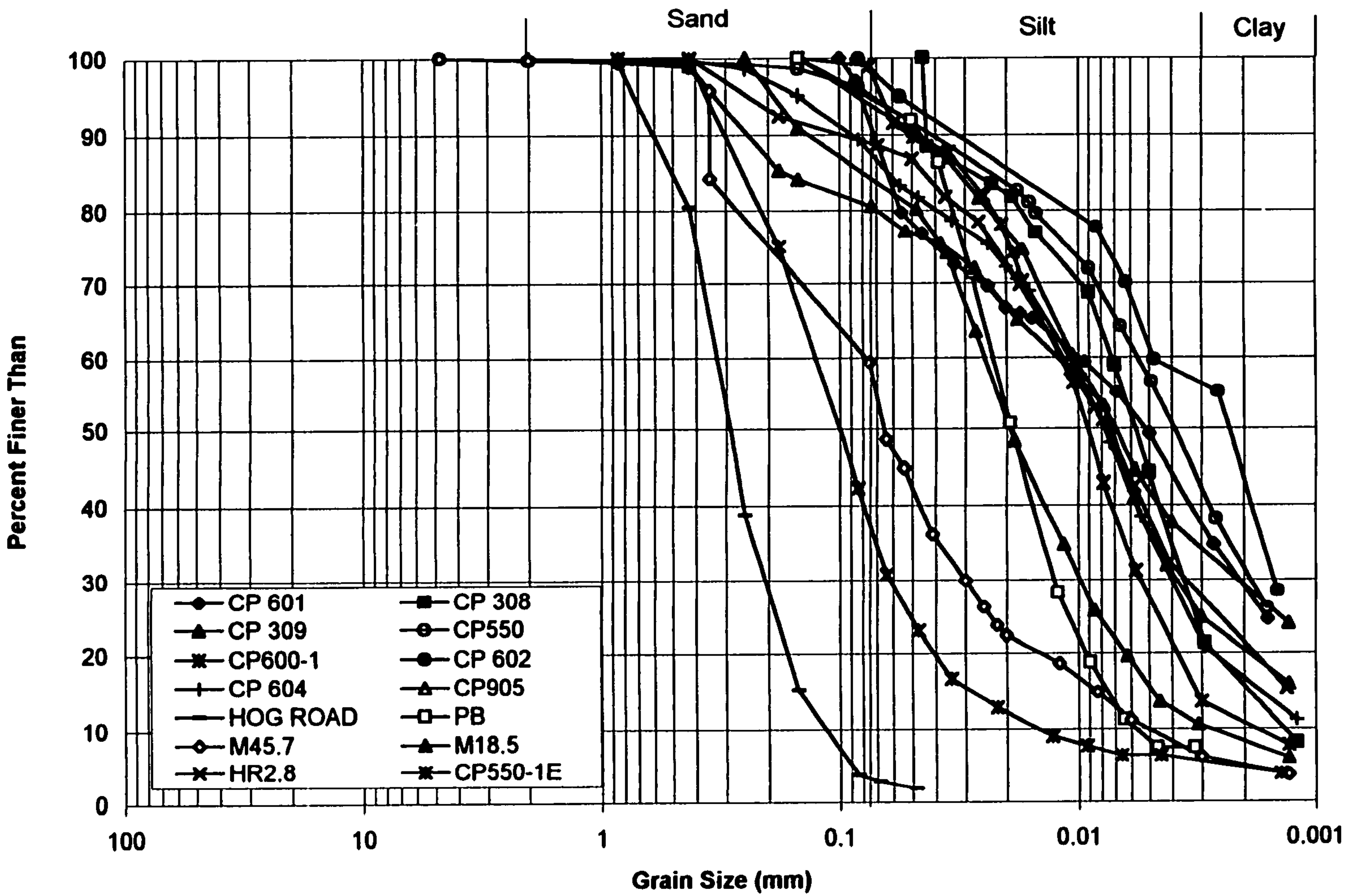


Figure 6.1. Grain size results for the Morkill River valley

6.3 Atterberg Limits

Samples taken from sites visited during the field program were tested for plasticity using Atterberg Limit tests (ASTM, 1997c). The results of the Atterberg Limit tests are presented on Figure 6.2.

As seen on the attached plot, Figure 6.2, the samples tested are grouped in two main classes. The largest class consists of inorganic silts of low to medium compressibility Mitchell (1993, Figure 10.16). The upper class, comprising sites CP 602 and CP 604, is of slightly higher plasticity, and classified as inorganic clays of medium plasticity (Mitchell, 1993).

As can be seen in Figure 6.2, the samples taken in the Morkill River valley have been compared to data presented by Bradshaw (1988), Mekechuk (1981) and MOTH (1995). The data taken from Bradshaw (1988) and Mekechuk (1981) have been collected in the area between McBride and Tete Jaune Cache in the Fraser River valley, while the data from MOTH (1995) have been collected from the arterial road that accesses the community of Crescent Spur, at the mouth of the Morkill River.

When taking into account the plasticity and the percentage of material passing the # 200 sieve, the activity of the soils can be determined. The activity provides an indication of the mineral composition of the clay fraction. The range in activities of the soils in the Morkill River valley is calculated to be from 0.23 to 0.55. These values of activities are considered to be in the range of values outlined by Mitchell (1993, Table 10.4) that correspond to kaolinite or illite clay minerals.

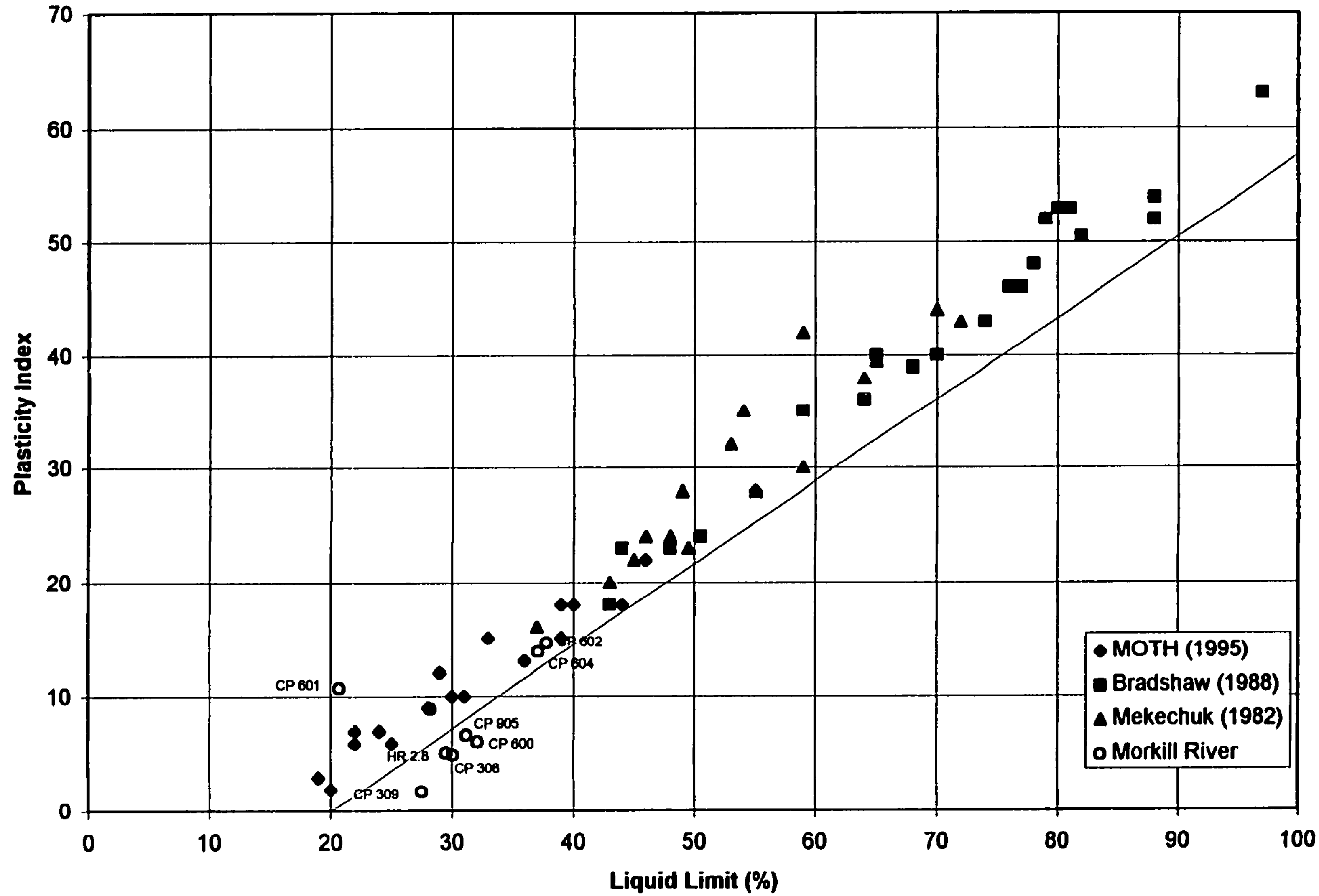


Figure 6.2 Atterberg Limits results for lake sediments in the Fraser River valley area

6.4 Density Tests

To supplement field density testing, as described in Section 5.2, cores obtained by field Shelby tubes and from block samples were tested in the laboratory. Samples consisted of approximately 35 mm diameter cylindrical samples that were approximately 75 mm in length. Dimensions of the samples were ascertained using digital calipers. All measurements were triplicated to obtain the average dimensions in each direction. Table 6.1 shows the maximum densities obtained by the rubber balloon method in comparison to the values obtained from the Shelby tubes and block samples.

	Rubber Balloon Density Results				Block/Shelby Tube Samples			
	Depth (m)	ρ Mg/m3	ρ_d Mg/m3	e	Depth (m)	ρ Mg/m3	ρ_d Mg/m3	e
CP550-1	0.3	1.85	1.53	0.73		-	-	-
Papa Bear	0.96	1.95	1.52	0.74		-	-	-
Morkill18.5	0.35	1.96	1.68	0.58	0.4	1.96	1.62	0.64
CP308-4	0.72	1.99	1.56	0.70	0.7	2.04	1.61	0.65
CP 309-1	0.45	1.88	1.53	0.73		-	-	-
Hog 3 km	0.5	1.77	1.60	0.66		-	-	--
CP 600-1	0.45	1.88	1.46	0.82		-	-	-
CP 601-3	0.55	2.04	1.75	0.51	0.7	2.2	1.95	0.36
Morkill45.7	0.88	1.86	1.47	0.80		-	-	-
CP 602-2	0.45	1.95	1.52	0.74	0.7	2.04	1.61	0.65

Table 6.1 Comparison of in situ and laboratory measured densities

As can be seen from the above table, the densities obtained from the Shelby tubes and block samples for sites CP308, CP601 and CP602 are up to 8 % higher than those reported by the rubber balloon density method. These differences may be attributed to operator error in collecting the samples, sample disturbance in the balloon **densities** or the location from which the sample is obtained. There is up to a 0.3 metre depth difference between the block sampling location and the balloon density location. This small difference in depth can account for differences in density shown above.

The values of dry density presented in Table 6.1 yield initial void ratio estimates of the undisturbed soils in the Morkill River valley from 0.36 to 0.82. The specific gravity value for quartz, 2.65, was utilized in the void ratio calculations. Due to this assumption, void ratio values do not account for the amount of calcite in the samples which totals up to 11 %. Since the specific gravity of calcite is 2.72, the values of void ratio may be a few thousandth parts lower, but are assumed acceptable for this study. The following typical values of void ratio for natural soils:

Soil	e_{Max}	e_{Min}	Source
Uniform sand	0.85	0.51	Terzaghi et al (1996)
Mix-grained sand	0.67	0.43	Terzaghi et al (1996)
Inorganic silts	1.1	0.4	Lambe and Whitman (1969)
Silty sand	0.9	0.3	Lambe and Whitman (1969)
Glacial clay	1.2	0.6	Terzaghi et al (1996)

Table 6.2 Typical values of void ratio for natural soils

The lowest value of void ratio obtained was 0.36 for sample 601. This sample is a sandy silt and the void ratio is considered to be at the low end of the range of expected void ratios and therefore these soils would be classified as very dense. The largest value of void ratio obtained was the value of 0.82 for the clayey silt at CP 600. At this void ratio the clayey silt is described to have a medium relative density.

6.5 Frost Susceptibility

A frost susceptible soil is defined in terms of frost heaving and thaw weakening (Andersland and Ladanyi, 1994). Thaw weakening is described by McFadden and Bennett (1991) as the process, that occurs during spring thaw, by which frozen underlayers often prevent proper drainage, and the saturated surface layers become soft and incapable of supporting loads. Frost heave is described as the segregation of the soil due to expansion from ice lens formation. The processes of frost heave and thaw weakening will be further discussed in Chapter 7.

To quantify whether a soil will be susceptible to frost action, numerous criteria based on laboratory tests have been developed. Studies by Johnson et al. (1986) and by Chamberlain (1981) reviewed existing criteria and agreed that the system proposed by the US Army Corps of Engineers (1965) provided the most reliable results. Therefore, I consider that system in the classification of the Morkill River soils in terms of frost susceptibility.

The US Army Corps of Engineers (1965) frost design and soil classification system is based on a 3-level screening process. The first stage identifies the percentage of particles smaller than 0.02 mm using conventional gradation analyses. The second screening stage identifies the soil type based on the Unified Soil Classification System and puts the soil into one of six categories of frost susceptibility: negligible, very low, low, medium high, and very high. A chart of this classification is presented in Figure 2-14 of Andersland and Ladanyi (1994). As the possible degrees of frost susceptibility have a wide range for most soils, based on the first two levels of screening, the US Army Corps of Engineers (1965) recommends that freezing tests be performed when precise information on soil frost susceptibility is required (Andersland and Ladanyi, 1994).

The frost susceptibility of the samples that I tested for the Morkill River valley, based on the above outlined criteria, are presented in Table 6.3 .

Sample	% passing No. 200	USC Soil Type	Frost Susceptibility	Frost Group
CP 308	100	ML	Low to very high	F4
CP 309	85	SM-ML	Very low to very high	F4
CP 550	39	SP-SM	Very low to very high	F4
CP 600	100	ML	Low to very high	F4
CP 601	92	ML	Low to very high	F4
CP 602	100	CL	Very low to very high	F4
CP 604	90	CL	Very low to very high	F4
CP 905	95	ML	Low to very high	F4
Hog Road	3	SW	Very low to high	S2
Morkill 18.5 km	81	ML	Low to very high	F4
Morkill 45.7 km	37	SM	Very low to high	F4
Papa Bear	95	ML	Low to very high	F4
Hellroaring Rd.	89	ML	Low to very high	F4

Table 6.3 **Frost susceptibility of Morkill River soils based on US Army Corps of Engineers Classification System**

A more recent approach for predicting frost heave susceptibility of soils (segregation potential) was based on parameters derived from the specific surface area and mineral content of the fines fraction of the soil (Davila et al, 1992; Davila, 1992). Davila et al (1993) related these same parameters to the liquid limit of the fines fraction of the soil and the percentage of clay in the fines fraction of the soil. Using samples from the Morkill River valley in which 100% of the material passed the 75 μm sieve and applying them to Davila et al's (1993) segregation potential curves, the values presented in Table 6.4 are obtained.

Sample	Segregation Potential (mm^2/s °C)
CP 308	22 (10^{-4})
CP 600	19 (10^{-4})
CP 602	11 (10^{-4})

Table 6.4 **Segregation potential for selected Morkill River soils**

Typical values reported for segregation potential (Nixon, 1987) show an expected range of 0 to 70 mm^2/s °C for silty sands, sandy silts and tills and a range of 50 to 200 mm^2/s.°C for clays and clayey silts.

Based on both of the above criteria, the majority of soils in the Morkill River valley would be rated to have a low segregation potential and thus a low susceptibility for frost heave. The total frost susceptibility requires further laboratory testing to investigate the effects of thaw weakening. Laboratory testing is presented in the next section.

6.6 Freeze/Thaw Testing

In order to supplement the index frost susceptibility tests, a modified test was conducted to ascertain the effects of cycles of freeze and thaw on two soil samples taken from the Morkill River valley. The test consisted of undertaking unconfined compression tests on samples subjected to 0, 1, 2, 5 and 10 cycles of one-dimensional freeze and thaw.

Samples chosen for testing were trimmed to approximately 35 mm diameter with an approximate height to diameter ratio of 2:1. All samples were measured, weighed and moisture samples taken from shavings prior to testing. In preparation for freezing, samples were encased with a weak rubber membrane and metal end caps. The purpose of the membrane was to minimize the loss of moisture during the cycles of freeze and thaw and during strength testing. Metal end caps were used to provided adequate thermal conductance during the freezing process.

In order to simulate one-dimensional freezing of the soil samples, each set of two samples was placed in a Styrofoam casing (Figures 6.3 and 6.4). Each casing was sealed with Styrofoam at the bottom with the top remaining open so that the top of the sample would be exposed to the ambient air temperatures. Samples were placed in a freezer maintained at -20 °C for a period of at least 12 hours and then removed and let to thaw in a room maintained at 100% relative humidity. Samples remained in the Styrofoam casing throughout the cycles of freeze and thaw.

Once samples had undergone the required cycles of freeze and thaw, unconfined compression tests were conducted according to ASTM D2166 (ASTM, 1997e). The testing apparatus was set for a strain rate of 6.1 mm/min. which corresponded to approximately 0.77 to 0.81 % axial strain for the samples tested. This strain rate was maintained for all tests.

Figure 6.5 shows the results of the freeze-thaw cycles on the unconfined compressive strength of the samples. As can be seen, after one cycle of freeze and thaw, there was a significant decrease in the strength of the samples.

The results also indicate a small increase in Unconfined Compressive Strength after 5 cycles of freeze/thaw for sample 601 and after 2 cycles of freeze/thaw for sample 602. I expect that this increase represents minor thaw consolidation of the sample and thus a corresponding minor increase in strength.

The results of the Unconfined Compression tests further enhance the frost susceptibility classification of the soils. Based on criteria for Unconfined compression tests on cohesive soils outlined in Table 7.1 of Terzaghi et al (1996), the soils from CP 601 and 602 are reduced from a relative density of very stiff to soft after one cycle of freeze thaw.

As shown in the photos in Figures 6.8 and 6.9, the soils from site 601 and 602 acted differently when subjected to cycles of freeze and thaw. Samples from site 601 appeared well bonded with trace amounts of excess ice after 10 cycles, whereas, after 10 cycles of freeze/thaw, the samples from site 602 exhibited stratified ice formations and segregation. Upon thawing the samples shown in the photos, the sample from CP 602 crumbled into four pieces. The samples from CP 601 remained intact but broke apart readily under an applied load as the calcite bonds at the grain contacts had been broken during the expansion of the soil structure during freezing.

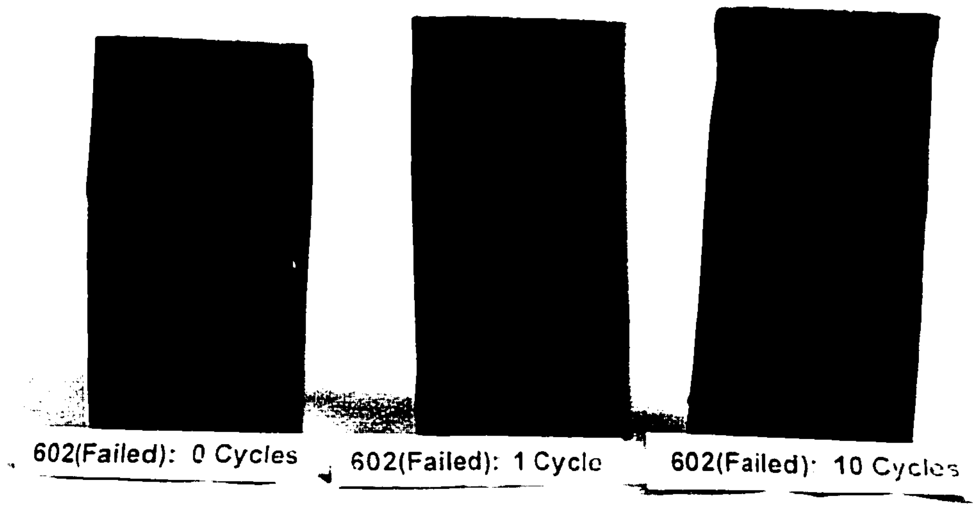


Figure 6.6 Samples 602: Failed Unconfined Compression Test samples

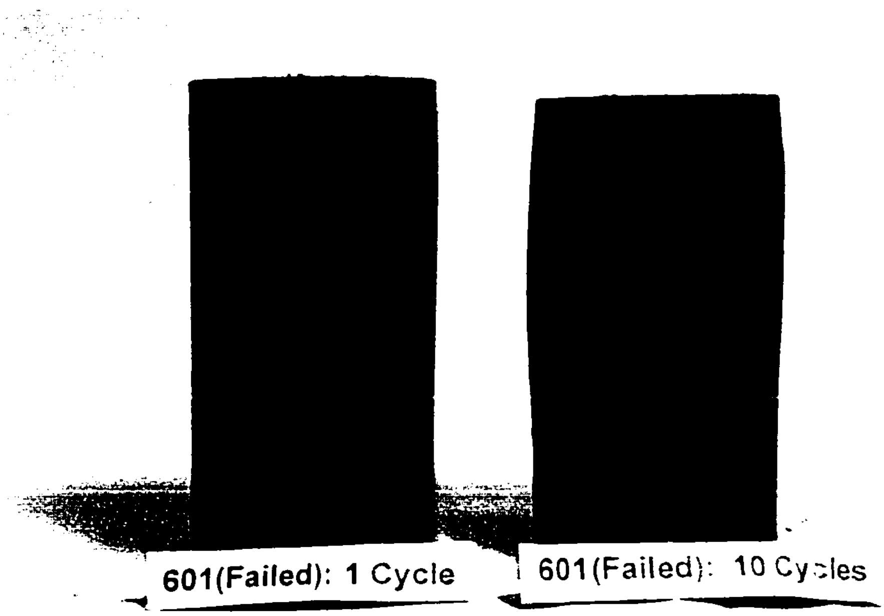


Figure 6.7 Sample 601: Failed Unconfined Compression Test samples

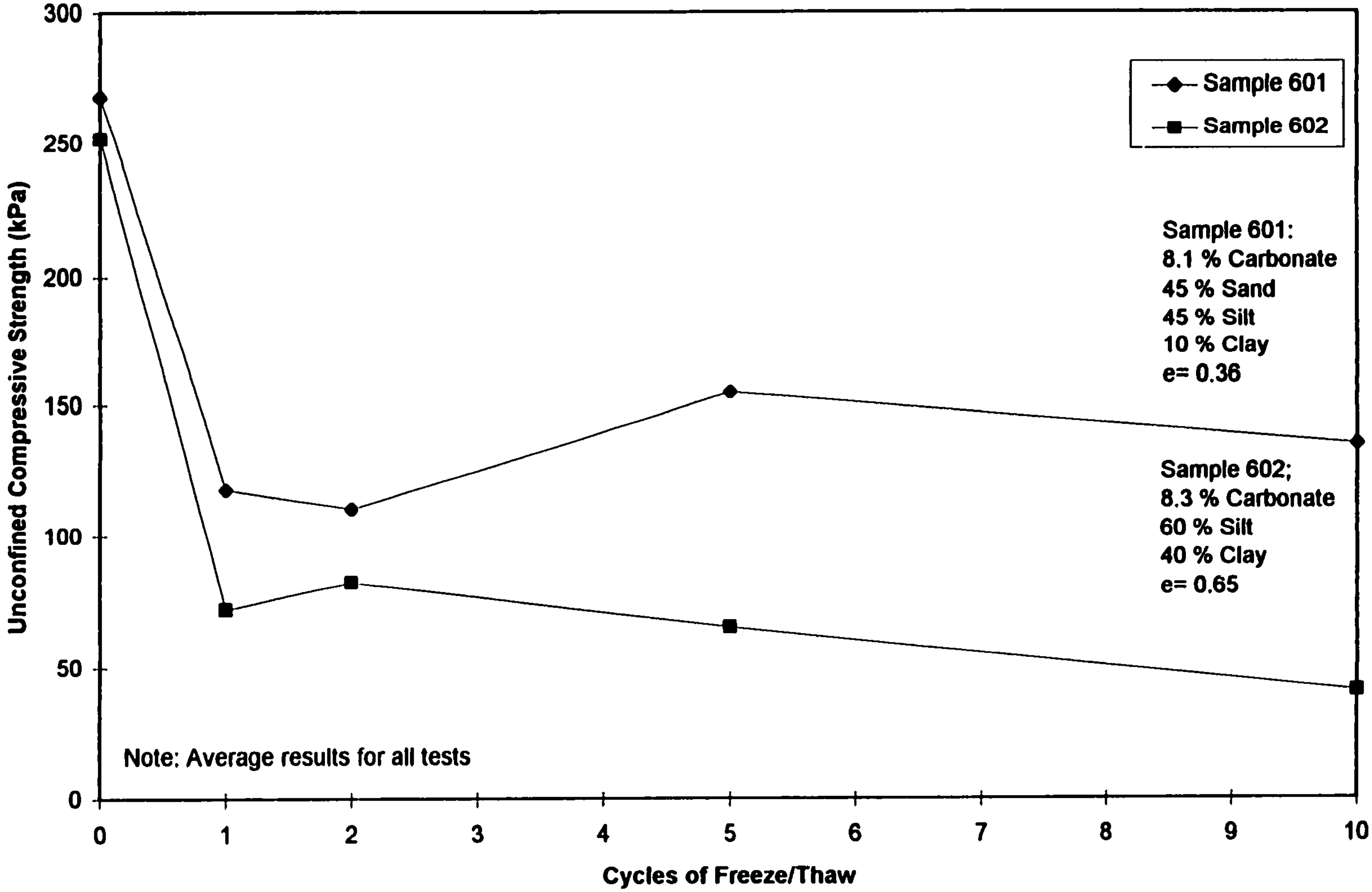


Figure 6.5 Results of Unconfined Compression Tests on samples subjected to cycles of freeze/thaw

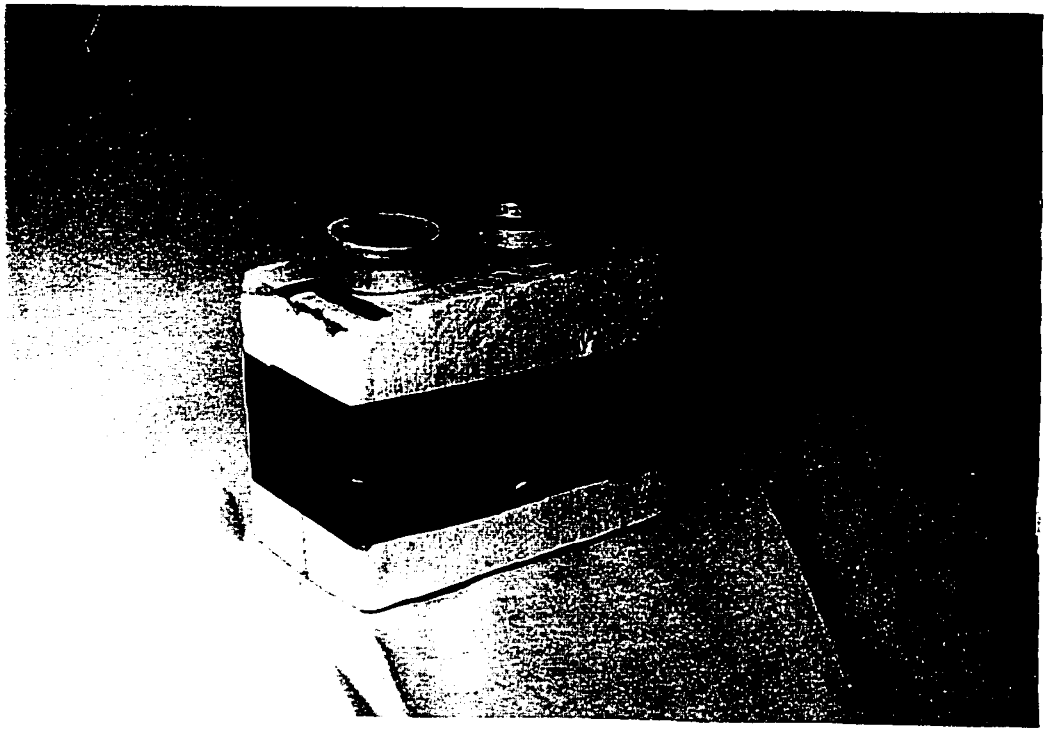


Figure 6.3 Cyclic freeze/thaw samples in freezing mould

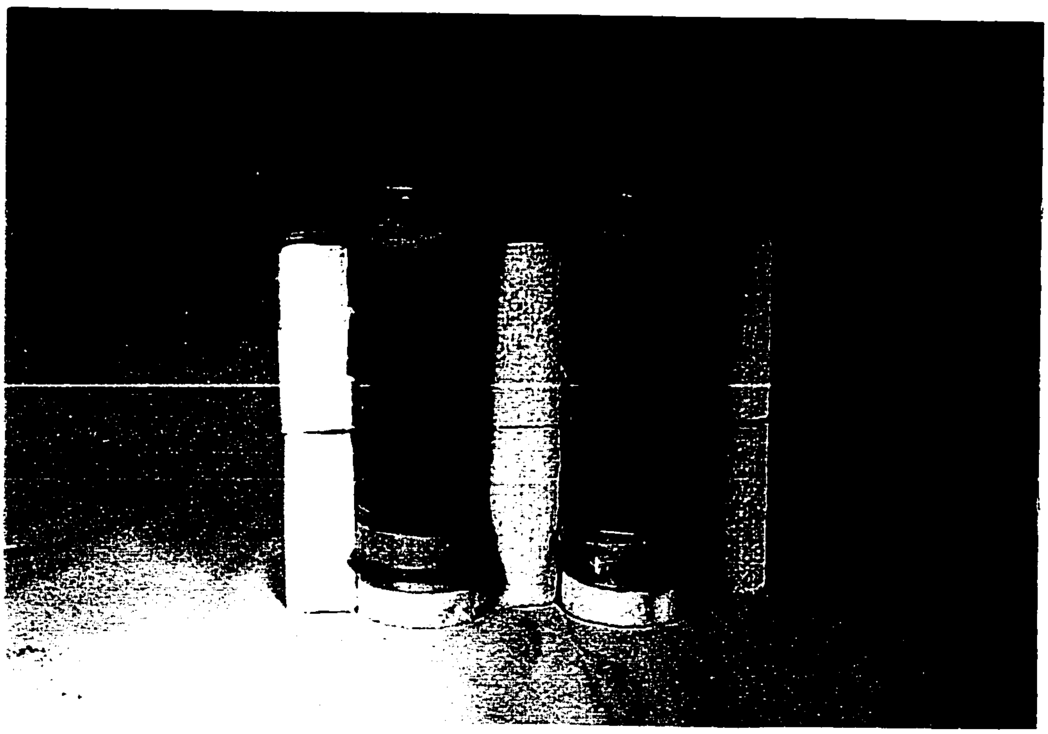


Figure 6.4 Cyclic freeze/thaw samples in half of freezing mould

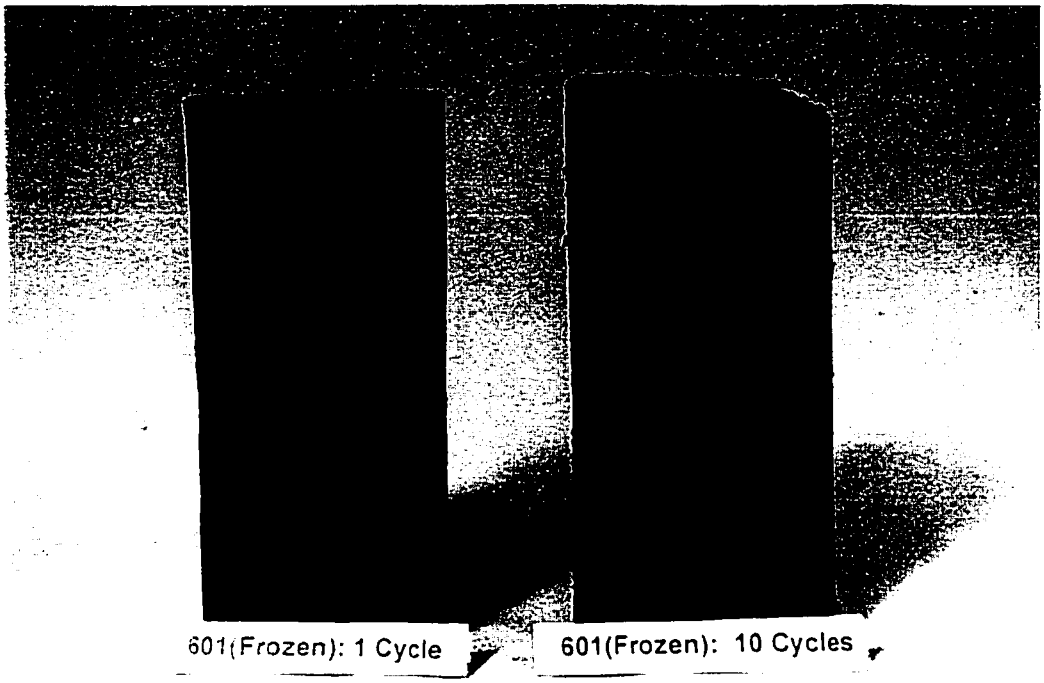


Figure 6.8 Sample 601: Cross section of frozen samples

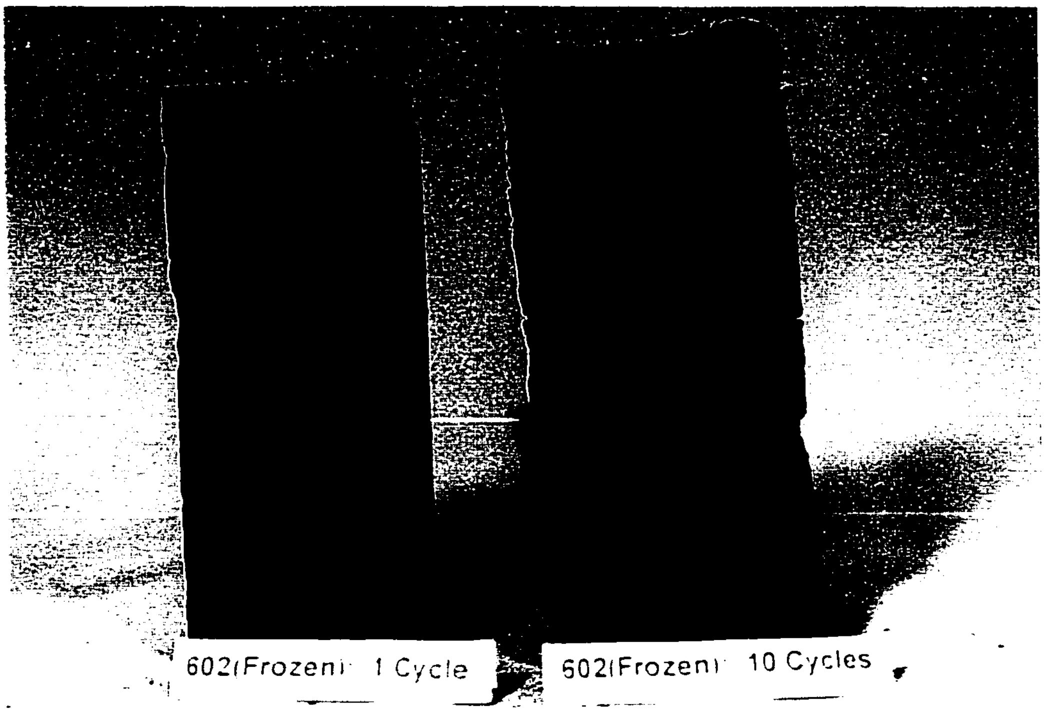


Figure 6.9 Sample 602: Cross-section of frozen samples

6.7 *Calcium Carbonate Determination*

Laboratory testing of the carbonate content of the soils was undertaken to provide a quantitative correlation between the decrease in density and carbonate content with depth observed in the field program. As there were a significant number of samples to test, a simple and reliable method of carbonate determination was required.

Cheney et al, (1982) provide a summary of laboratory methods used in order to determine the calcium carbonate content in soils. Each of the test types outlined was described briefly and the advantages and drawbacks were described. The methods outlined included the following: Atomic absorption spectrophotometry, EDTA titration, Calcium-specific ion electrode, Vacuum-distillation and titration method, Gravimetric method, Acid-soluble weight loss methods and Volume calcimeter method. More recently, Boone and Lutenegger (1997) described the use of gasimetric and a Chittik apparatus for the determination of carbonates. These methods all vary in their level of accuracy and cost, but perhaps the main determining factor in the choice of method is availability of equipment.

The method chosen for the calcium carbonate determination was a variation on the vacuum-distillation and titration method. This type of test was chosen because of its good relative accuracy, low to moderate costs and availability of equipment at both the University of Northern British Columbia (UNBC) Soils laboratory and at the University of Alberta. The test procedure used was a modified version of the one outlined by Bundy and Bremner (1972). A brief description of the test methodology and theory is presented below as outlined by Bundy and Bremner (1972):

Basically soil samples are treated with strong acid to dissolve resident carbonate material and generate CO_2 gas. The CO_2 (g) evolved from the sample is subsequently collected in a solution containing strong alkali (base) of known concentration. A back titration is then performed to determine the amount of

CO_2 collected and thus estimate the amount of carbonate-carbon contained in the soil sample.

The deviation from the standard method outlined by Bundy and Bremner (1972) was the use of a rubber septum and syringe apparatus to de-air the test flask. A schematic of the apparatus used is shown in Figure 6.10. In the standard procedure, a pump is used to create a system vacuum in which to facilitate the reaction of the CO_2 and the standardized base solution. This has limitations as it would only allow for one sample to be tested at a time. Up to nine samples were tested at a time using the apparatus shown in Figure 6.10. In order to create a vacuum for the system, the rubber stopper, shown in the diagram was thinly coated with vacuum grease and inserted into the neck of a 250 ml Erlenmeyer flask and rubber bands were used to secure the stopper in place. The air in the flask was then evacuated using a 60 ml syringe. Once there was significant resistance in the evacuation of air, I considered that a vacuum had been created. At the end of each test when each stopper was removed, audible observations were made as to whether a vacuum had been maintained during the test.

The results of the calcium carbonate determination on samples obtained during the field program are presented below in Table 6.5. The following table outlines the range in carbonates found in the profiles at each location.

	Carbonate Content (%)	
Location	Minimum	Maximum
CP 308	1.5	6.8
CP 309	0.6	8.4
CP 550	8.7	11.1
CP 600	6.1	9.2
CP 601	6.2	8.9
CP 602	6.7	9.3
Hog Road	0.4	5.2
Morkill 18.5 km	7.8	8.7
Morkill 45.7 km	0.6	6.4
Papa Bear	8.7	11.1

Table 6.5 Laboratory determined carbonate contents for field soil profiles

As can be seen from the above table, maximum values of carbonates of 10-11% are obtained based on the laboratory program. A classification scheme for calcareous soils presented by Fookes (1988) was based on grain size and unconfined compressive strength. The majority of soils in the Morkill River valley would then be classified as very stiff, non to weakly calcareous silts to muds. Fookes (1988) suggests a minimum carbonate content of 50 % in order for a soil to be classified as a carbonate soil. Therefore, the soils in the Morkill River valley cannot be classified as carbonate soils.

Results of carbonate content have been reported to one decimal place for purposes of this study. The laboratory procedure manual indicates that the procedure can detect minute amount of carbonate (<0.3 mg/g). Even though this accuracy is theoretically possible, I consider possible sources of error in the preparation of samples and the titration to limit the accuracy to 0.1 %.

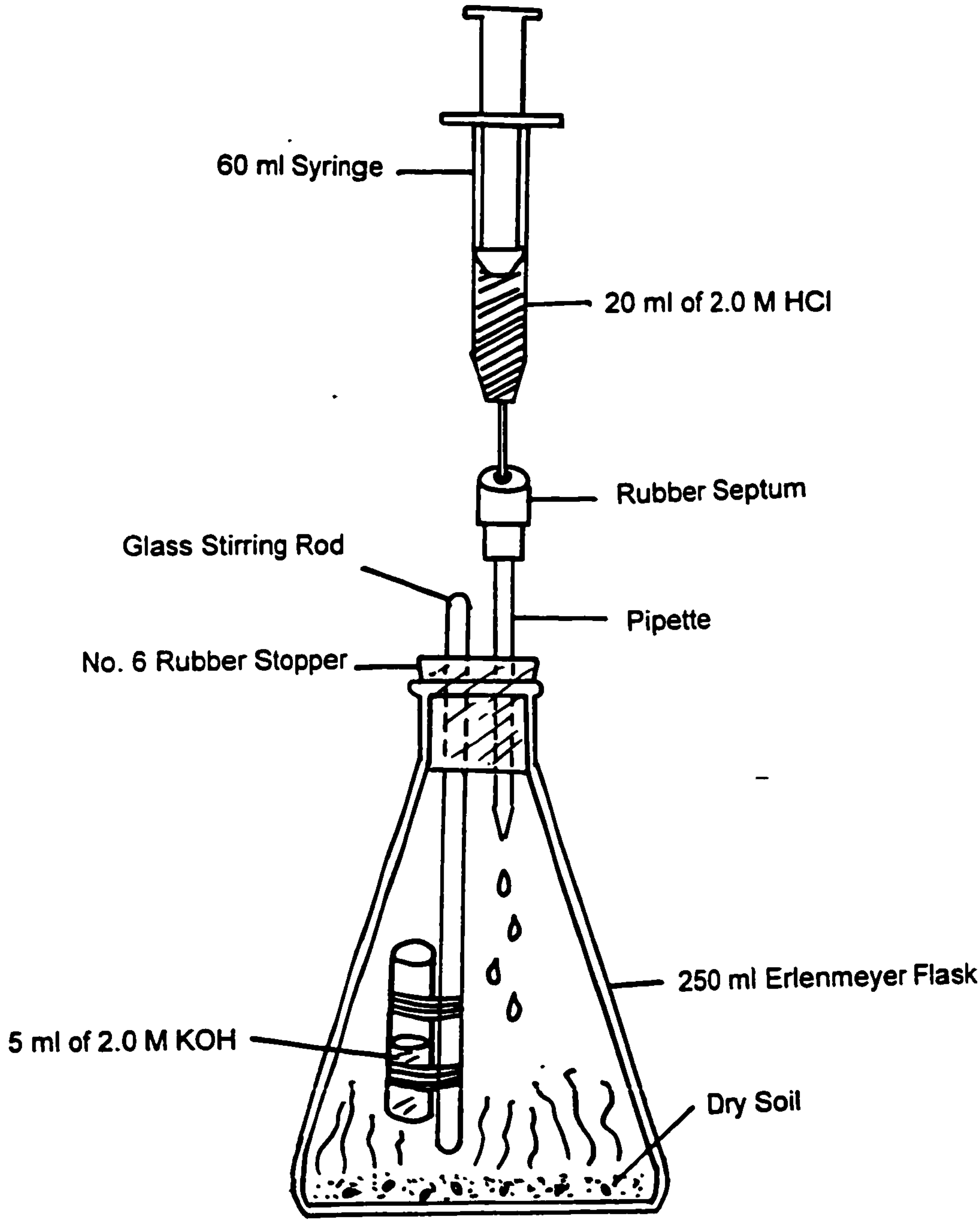


Figure 6.10 Schematic diagram of calcium carbonate determination apparatus

6.8 *Scanning Electron Microscopy*

Scanning electron microscopy (SEM) was used to answer questions about the occurrence of carbonates in the soil matrix. Two possible hypotheses were that the carbonates occurred as clasts of limestone in the soil matrix, or that the carbonate had been precipitated from groundwater and was acting as a cementing agent at grain contacts.

Figures 6.11 and 6.12 show photos obtained looking at Sample 601, normal to and parallel to the bedding plane, respectively. As can be seen from the photo, calcium carbonate is not found in the form of grains or clasts as part of the soil matrix. The electron diffraction spectra taken on various grains throughout the soil matrix indicate that the silt size particles consist of predominantly quartz grains with some feldspars. These observations are consistent with the known bedrock geology of the area which contains both quartzitic and feldspathic sandstones. Clay size quartz grains ($<2\mu m$) are also found to comprise a considerable portion of the area between the larger quartz grains. The clay is most likely kaolinite based on the electron diffraction results. The grain labeled "Calcium Carbonate" in Figure 6.12 is a grain of quartz with a very high reading of C,O, and Ca when analysed by electron diffraction.

The electron diffraction spectra also noted trace amounts of C, O and Ca at all areas analyzed. This observation, coupled with the results of the carbonate content determination, supports the view that there are carbonates located in the soil matrix as a cement, precipitated from local ground water.

A discussion of the origin and dissolution of the carbonate in the soil matrix will be given in Chapter 7.

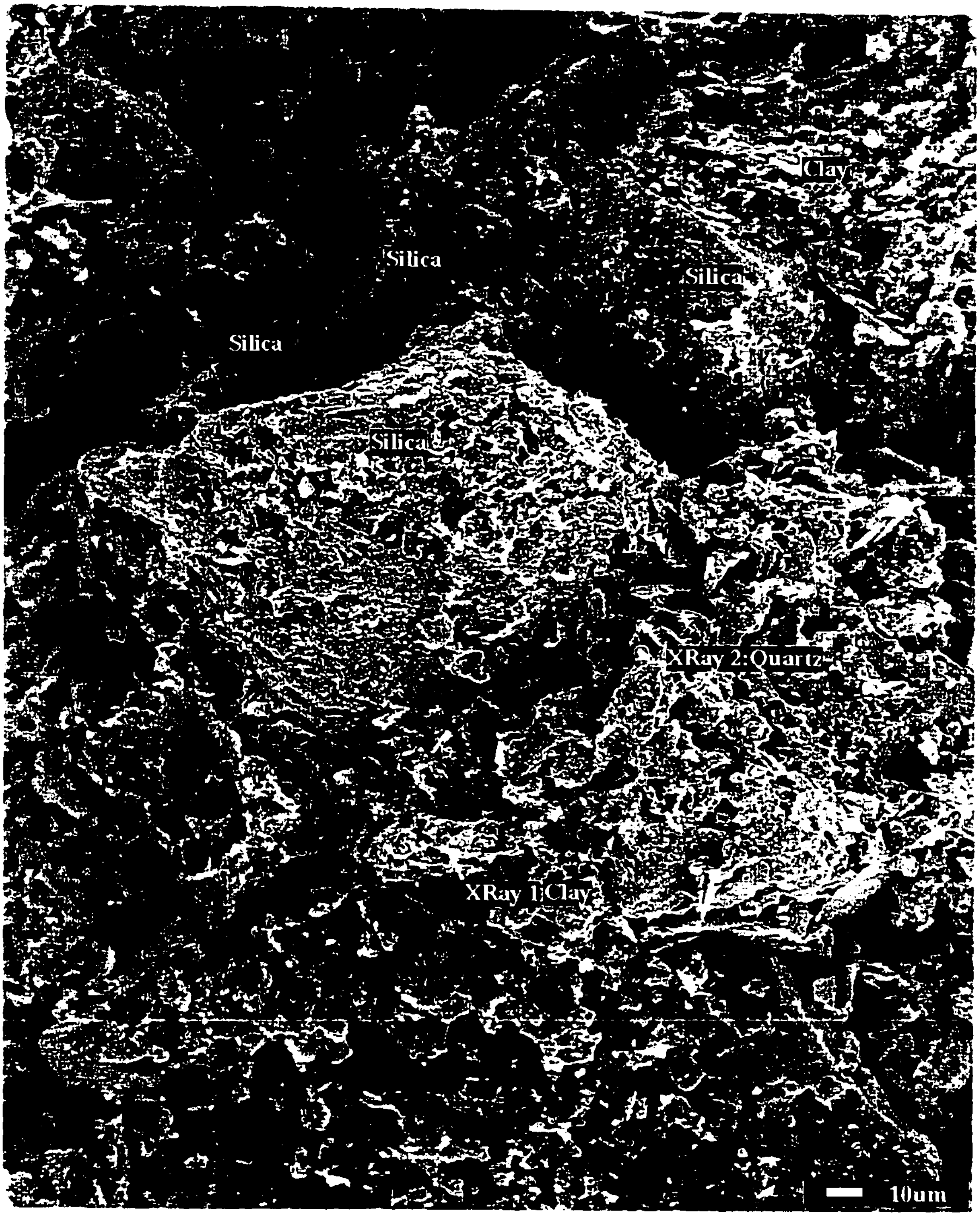


Figure 6.11 Sample 601: Scanning electron microscope image perpendicular to bedding (250X Magnification)

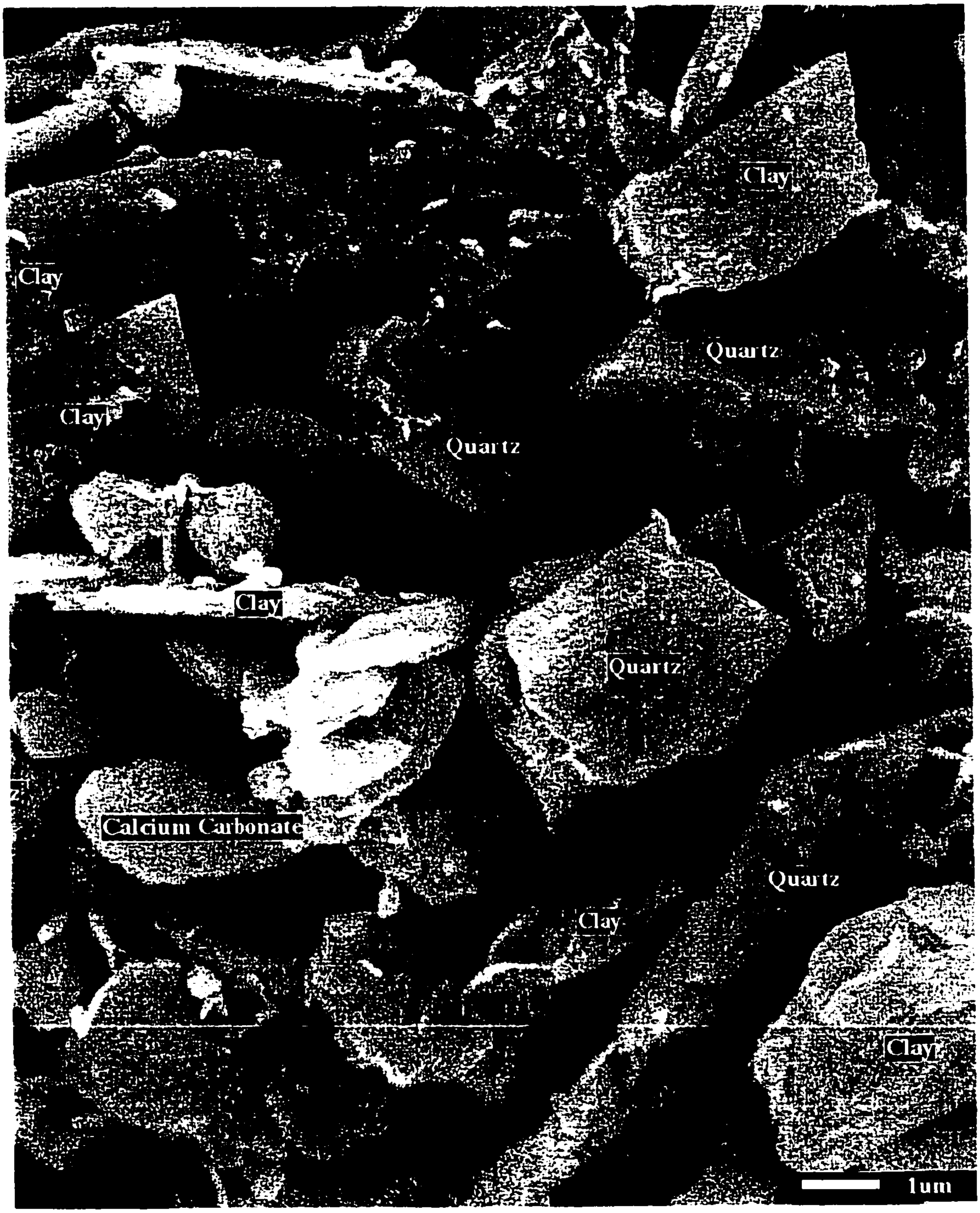


Figure 6.12 Sample 601: Scanning electron microscope image parallel to bedding (5500 X Magnification)

6.9 *Conclusions*

A summary of the results of laboratory tests on lacustrine sediments in the Morkill River valley is presented in Table 6.6.

I undertook Atterberg limit tests and hydrometer tests in order to gather index data for use in the classification of the soil in the Morkill River valley in accordance to the Unified Soil Classification System. Based on this system, the soils in the Morkill River valley were predominantly sandy silts, silty sands and clayey sillts, with poorly graded sands located at the Hog road, CP 550 and M45.7. The plasticity of the cohesive soils indicates that the silts and clayey silts are low plastic. Figures 6.1 and 6.2 provide graphical indications of the grains size analyses and Atterberg Limits, respectively.

Density results were obtained in the field using a rubber balloon apparatus (ASTM, 1997b) and in the laboratory using samples obtained from Shelby tubes and block samples obtained during the field program. In situ densities for the lacustrine sediments ranges from 1.77 Mg/m^3 to 2.20 Mg/m^3 with corresponding void ratios of 0.36 to 0.82. The lowest void ratios correspond to minimum reported values of void ratios for inorganic silts and silty sands and these soils are therefore considered to be very dense. The in situ densities obtained from block samples and Shelby tubes are on average 15 % more than the densities obtained by the rubber balloon method. This difference can be attributed to the disturbance of soils during excavation for the rubber balloon test and inherent errors in operating equipment under field conditions.

Frost susceptibility of the lacustrine sediments was addressed using both the index properties of the soils and laboratory strength testing. Using the US Army Corps of Engineers (1965) classification criteria, coupled with Davila et al's (1993) correlations for segregation potential, the soils tested are considered to have a moderate to very high susceptibility to frost action and a low susceptibility to frost heave.

The laboratory testing for the effects of frost action on the soils consisted of unconfined compression tests conducted on samples from CP 601 and CP 601 that had been subjected to 0, 1, 2, 5 and 10 cycles of one-dimensional freeze and thaw. Samples exhibited a 50% decrease in strength after one cycle of freeze and thaw. Visual observations of the samples tested showed that the structure of the sandier sample, CP601, appeared well bonded after 10 cycles of freeze and thaw, while the structure of CP 602, a sample with 43 % clay size fraction, exhibited stratified ice formation and segregation after 10 cycles of freeze and thaw.

In order to quantify the carbonate contents in the samples taken when obtaining the field profiles, a vacuum distillation/titration procedure was used to determine the carbonate content of the lacustrine soils in the Morkill River valley. Carbonate contents of 5.2 to 11.1 % were obtained for unweathered samples. These maximum carbonate contents, along with the unconfined compression test results of the intact samples of approximately 250-270 kPa, enable me to classify the soils tested as very stiff, non to weakly calcareous silts to muds according to Fookes (1988) classification.

Scanning electron microscope (SEM) was used to observe the structure of the lacustrine sediments for CP 601 and to make observations as to the location of the carbonates in relation to the soil matrix. The SEM photos, Figures 6.11 and 6.12, did not show any carbonate grains. As well, electron diffraction on soil grains in the photos indicated trace amounts of $CaCO_3$ in the soil matrix. These observations, along with the results of the carbonate content determination and the low void ratios, supports the view that there are carbonates located in the soil matrix as a cement, precipitated from local groundwater or springs. Calcite present as a cement increases the density and strength of the sediment while decreasing the porosity.

Sample	Gradation			Atterberg Limits			UCS	Bulk Density	Void	$CaCO_3$ Content		Frost
	Sand	Silt	Clay	LL	PL	PI	Classification	(Mg/m^3)	Ratio	Min,	Max,	Susceptibility
CP 308	0	84	16	30.1	35	5.1	ML	2.04*	0.65	1.5	6.8	Low to very high
CP 309	15	77	8	27.5	29.2	1.8	SM-ML	1.88	0.73	0.6	8.4	Very low to very high
CP 550	61	35	4	NP	NP	NP	SM	1.85	0.73	8.7	11.1	Very low to very high
CP 600	0	89	11	32.1	26	6.1	ML	1.88	0.82	6.1	9.2	Low to very high
CP 601	45	45	10	28.2	19.3	8.9	ML	2.2*	0.36	6.2	8.9	Low to very high
CP 602	0	57	43	37.8	23.2	14.6	CL	2.04*	0.65	6.7	9.3	Very low to very high
CP 604	10	73	17	37.1	23.3	13.8	CL	-	-	-	-	Very low to very high
CP 905	4	78	20	31.2	24.5	6.7	ML	-	-	-	-	Low to very high
Hog Rd.	97	3	0	NP	NP	NP	SW	1,77	0.66	0.4	5.2	Very low to high
M18.5	19	51	30	20.7	31.4	10.7	ML	1.96	0.58	7.8	8.7	Low to very high
M45.7	63	37	0	NP	NP	NP	SM	1.86	0.80	0.6	6.4	Very low to high
Papa Bear	5	95	0	NP	NP	NP	ML	1.95	0.74	8.7	11.1	Low to very high
Hellroaring	11	68	21	29.5	24.5	5.2	ML	-	-	-	-	Low to very high

* Laboratory sample
NP Non plastic

Table 6.6 Summary of laboratory testing results

Chapter 7: Landslide Processes

7.1 Introduction

The nature of the weakly cemented, fine grained soils, along with the climatic factors in the Morkill River valley, have a significant effect on the strength properties of the soils in area. As shown in the laboratory testing (Chapter 6) and the field testing programs (Chapter 5), there is an observable effect of frost action and loss of calcium carbonate on the strength of the soils.

The following sections detail the contribution of mechanical weathering (Section 7.3), chemical weathering (Section 7.3) , and erosion (Section 7.4) and their effects on the shear strength of soil and subsequent slope instability. These contributions will be described with respect to the types of landslides found in the Morkill River valley (Section 7.5).

7.2 Effects of Mechanical Weathering

Mechanical weathering processes include unloading, thermal expansion and contraction, frost action, colloidal plucking and organic activity (Mitchell, 1992, p. 43). The most prevalent mechanism in the Morkill River valley is frost action.

7.2.1 Frost Action

The processes of freezing and thawing of seasonally frozen ground have direct and detrimental effects on the shear strength of soil and slope stability. The expansion of the soil matrix due to freezing porewater, the disaggregation and uplift of the soil mass due to frost heave and the generation of excess pore pressures and subsequent weakening of the soil during thaw all contribute to the loss of shear strength in fine grained soils.

During prolonged periods of subzero temperatures, frost penetrates into the subsoil and freezes the porewater contained in the soil matrix. The depth of frost penetration varies depending on the thickness and type of ground cover, moisture content and grain size of the soils. Lack of ground cover, low moisture content and high fines content of the soils enhance the frost penetration.

Frost Heave

The freezing of ground in fine grained soils is often accompanied by the formation of ice layers or lenses that range from one millimetre to several centimetres thick. Ice lenses form predominately in silty soils. As the soil freezes, the freezing front migrates downwards in the soil and water is drawn toward the freezing front from below. As the water reaches the freezing front, horizontal ice lenses are formed perpendicular to the freezing front. These lenses can be up to tens of centimetres in thickness and exert substantial heave forces. Observations based on the weight of buildings known to have been lifted by frost-heaving indicated heave forces approaching 700 kPa (Andersland and Ladanyi, 1994). During this process, the ground surface may heave by as much as several tens of centimetres and the overall increase can be many times the nine percent volume increase that occurs when water freezes (Mitchell, 1992).

Three factors are necessary for ice lens formation and frost heave (Mitchell, 1992):

1. A frost susceptible soil
2. Freezing temperature,
3. Supply of water.

Frost creep occurs when soil freezes and heaves perpendicular to the slope and upon subsequent thawing, large voids are left by the melting ice and there is a general loss of support. Thaw causes soil to settle vertically (Tart, 1996) and flow. Evidence of the effects of frost heave and creep are discussed in Section 7.4 and shown in Figure 7.16. The profile at site CP 308 (Figure 7.1) , shows the upper 0.5 metres of soil in the exposure is broken down due to ice lens formation parallel to the slope and loss of calcium carbonate by dissolution and leaching.

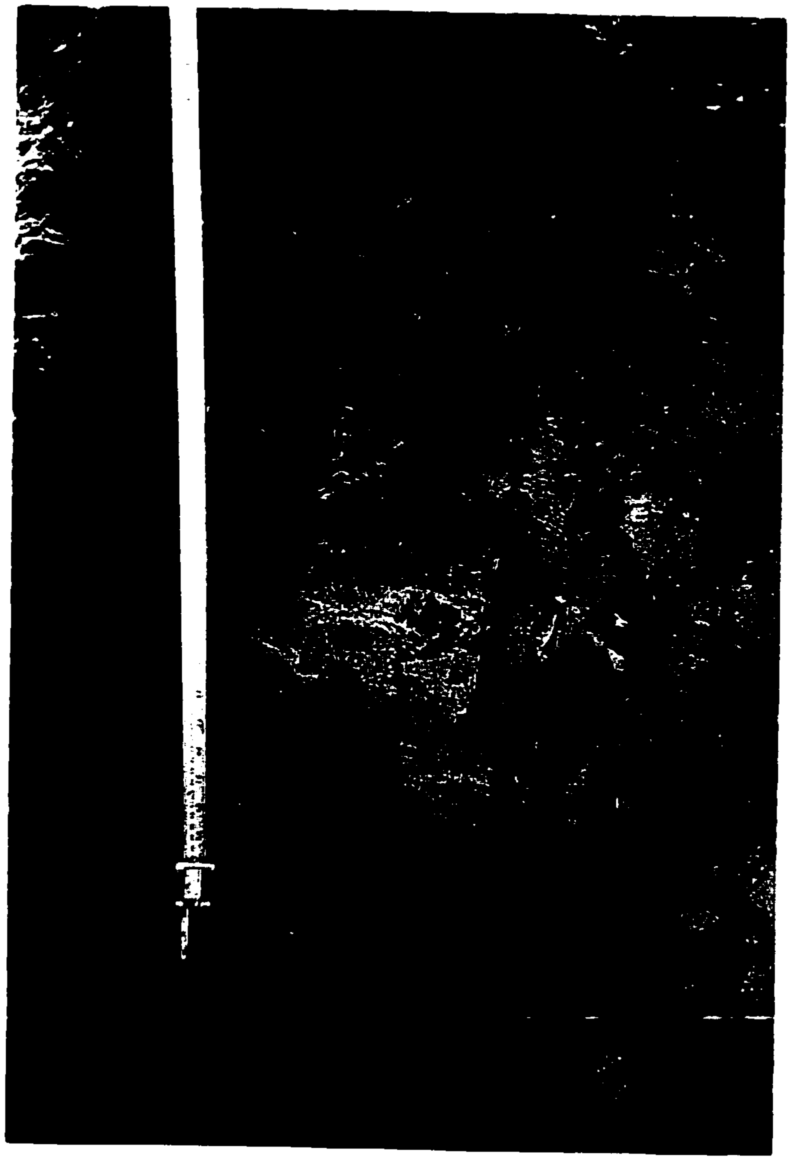


Figure 7.1 Profile at CP 308 showing evidence of disaggregation of soil due to ice lense formation in upper 0.5 metres

Thaw Weakening

Thaw weakening and the corresponding loss of shear strength in fine grained soils is a significant contributor to instability in seasonally frozen slopes in the Morkill River valley. Thaw weakening is the process in which the thawing of ice in the soil at a rate faster than meltwater can drain leads to an increase in pore pressure and an overall decrease in strength (Phukan, 1985). This loss of shear strength leads to problems in slope stability.

There are two primary factors that cause thawing in frozen ground (Phukan, 1985, p. 269):

1) Disturbance of the soil surface conditions by destruction, removal, altering, or covering the surficial vegetative mat;

2) Heat input to the frozen ground from a heated structure resulting in a rise in the ground operational temperature to above 0°C or 32°F. These disturbances are often the result of road construction, heated oil pipeline construction, removal of natural vegetation cover, snow cover and increased temperature variations in the underlying soil.

Thawing soils are classified into three categories by Phukan (1985, p. 269):

1) Thawing soils of no concern,
2) Thawing soils of concern (silty soils),
3) Thawing soils of great concern (ice rich silty soils or fine grained soils)

The majority of soils in the Morkill River valley, based on the grain size distributions presented in Figure 6.1, fall in the latter two categories. The frost susceptibility of the soils in the Morkill River valley is discussed in Section 6.5. As shown in Section 6.6, the soils in the Morkill River valley exhibit a 40-50% loss in Unconfined Compressive Strength after a cycle of freeze and thaw. This is thought to represent the breaking of calcite bonds due to the 9% volume expansion of water on freezing in siltier soils and the disaggregation due to ice lens formation in the silty samples with a higher clay content.

7.3 *Effects of Chemical Weathering*

As discussed in Chapter 3, chemical weathering is a dominant factor in the breakdown of soils in the Morkill River valley. Weathering as a result of the dissolution and subsequent leaching of calcite cement is considered. Weathering processes such as oxidation, carbonation and hydration also contribute to the overall chemical weathering process but will not be discussed within the scope of this study.

7.3.1 Leaching and Dissolution of Calcite

A full discussion of the leaching of calcite cement in soils of the Morkill River valley, begins with the origin and formation of the cementation bond. It has been suggested that cementation forms over long periods of time following sedimentation by precipitation of cementing agents in marine or arid environments, weathering, or by long-term crystal growth between grains (Bjerrum, 1967; Quigley 1968; Mitchell and Houston, 1969; Moum and Zimmie, 1972; Sangrey, 1972a,b; Fookes, 1988; Little, 1989, Boone and Lutenegger, 1997). The final structure of the soil is dependent on the balance of deposition, stressing and bonding rates, and mineralogy (Boone and Lutenegger, 1997). Processes of sedimentation and precipitation are described below.

Subglacial transport of carbonate rock debris produces abundant fine reactive particles (rock flour) which are susceptible to dissolution and precipitation (Fairchild, 1994). The most common mineral to be precipitated from glacial meltwater is calcite, as calcite is the least resistant of the secondary minerals to weathering (Brady, 1990, Table 2.2).

A number of processes allow reprecipitation of calcite in the glacial system: ripening, warming, freezing, the common ion effect, removal of $C0_2$ by organic and inorganic means, transpiration and skeletal biomineralization. The relative importance of these mechanisms had yet to be established (Fairchild et al., 1994).

Fairchild et al. (1994, p. 182) considered ripening to be the most prevalent mechanism in glacial meltwater environments and described the process as follows:

"Ripening is essentially a combination of dissolution and precipitation proceeding simultaneously. Ripening is a process that can only occur in saturated solutions in contact with material of extremely fine crystal size. Given that the finest materials dissolve most readily in (flowing) water, ripening is therefore most likely to occur in the porewaters of subglacially transported sediments freshly released from glacial ice. The extent to which ripening occurs will be critically dependent on the crystal size, distribution (abundance of the finest materials) and the extent of lattice defects in the crystals".

The pattern of distribution of carbonate content in the Morkill valley is not clear. The pattern of change in carbonate content appears related to distance from source rocks, to avenues of principal ice movement and to intensity of erosion (Merritt and Muller, 1959). The concentration of any given constituent in the basal load of a glacier may be expected to be depleted by deposition at a decreasing rate with increasing distance from the source and it may be conjectured that this is the principal process affecting change in carbonate content in areas of high lime till. (Merritt and Muller, 1959).

Studies of the formation of marl and tufa deposits in Alberta (Macdonald, 1982) show that springs supersaturated with calcium carbonate discharging from calcareous bedrock are a major source of calcium carbonate in soils. Borneuf (1982) and Gadd (1986) discussed the occurrence of springs in Alberta and the Canadian Rockies but did not provide locations of any such springs in the vicinity of the Morkill River valley. During my field investigation, I noted a seasonal groundwater discharge point at Kilometre 45 on the Morkill FSR in a layer of well graded gravel. In the gravel itself, a hard pan of cemented clasts had been formed. The unit ranged from 0.2 to 0.5 metres in thickness and approximately 15 metres in width .As can be expected, the location of springs originating along faults from the limestone of the lower Miette would be expected to have an impact on the calcium carbonate content in the vicinity of such a discharge.

Dissolution is the simplest process whereby minerals can be decomposed and involves water acting as a solvent (Summerfield, 1991). This process is accelerated by the presence of water, oxygen, and the organic and inorganic acids that results from the microbial breakdown of plant residues (Brady, 1990). The organic acids (produced by biochemical processes in the soil), sulphuric acid (produced by pyrite degradation) and acid rain, as well as other forms of anthropogenic acidification, must all play parts in the removal of carbonate from the near surface materials (Hawkins and McDonald, 1992).

Carbonic acid is probably the most important solvent of calcite and has a well known solution chemistry. The presence of carbonic acid (H_2CO_3) results in the chemical solution of calcite, as illustrated in the following reaction (Brady, 1990).

$$CaCO_3 + \underset{\underset{H_2O + CO_2}{\Uparrow}}{H_2CO_3} \rightarrow Ca^{2+} + 2HCO_3^-$$

Once dissolution has occurred, the calcite is remove from the soil structure by leaching. Leaching is described as the process whereby percolating water removes materials from the upper layers of a rock, soil or ore, and carries them away in solution or suspension (Clark, 1990). Studies by Merrit and Muller (1959), Dreimanis (1961), Quigley and Ogunbadejo (1972b), and Lutenegger (1995), have illustrated leaching of carbonates from the weathering zone. The depth and rate of carbonate removal by leaching are dependent on climate, vegetation, topographic position, depth to water table, carbonate content, ratio of magnesium to calcium carbonate, permeability and stratification of parent material (Merritt and Muller, 1959). Carbonate leaching from seepage may be an important mechanism in reducing shear strength and creating slope instability, both in surficial soils and in deeper failures with layers of higher permeability (Boone and Lutenegger, 1997).

During the field investigation in the Morkill River valley, I noted numerous examples of evidence of the leaching of carbonates. Visual evidence in the form of calcite precipitate formed at lower permeability interfaces (Figures 7.2, 7.3), carbonate root accumulations (Figure 7.4), and calcite-rich "lobes" of flowing soil (Figure 7.5) were observed during my field investigation in the Morkill River valley.

As discussed in Chapters 5 and 6, I attempted to quantify the effects of leaching during the field and lab investigations by addressing the correlation of carbonate content and in situ bulk densities in the field. Figures 7.6-7.8 show the data trends on the carbonate vs. density plots for the sites discussed in Section 5.3. As can be seen from the plots, although there is scatter for each site, there is a general linear correlation for the sites in Lakes A,B,D,E (Figure 7.6 and 7.7) that comprise predominantly silt size material. The profiles obtained from the sandier material, Lake C , (Figure 7.8) exhibit a slightly steeper trendline relationship. As there is much scatter in the data, the data trendlines show general trends, not precise relationships. The lines on Figures 7.6 to 7.9 have been manually drawn to represent these relationships. I hypothesize that the steeper gradient of the trendline for the sands represents the abrupt drop in carbonate content due to enhanced leaching in the higher permeability material.

The carbonate content with depth is qualitatively dependent on the grain size of the materials. In profiles with a relatively uniform grain size, such as profile CP 308 (Figure 5.2d.), there is an increase in $CaC0_3$ and density with increasing depth. As expected, there is local variation due to natural heterogeneity in soils. These variations account for anomalies in the profiles.

The profile at site CP550-1 (Figure 5.2.a) is an example of the effects of grain size on carbonate content. The soils in the profile increase in density with depth but decreased in carbonate content with depth. There is a corresponding increase in grain size with depth and it is therefore considered that leaching has a greater effect on the removal of calcite at depth due to the higher permeability

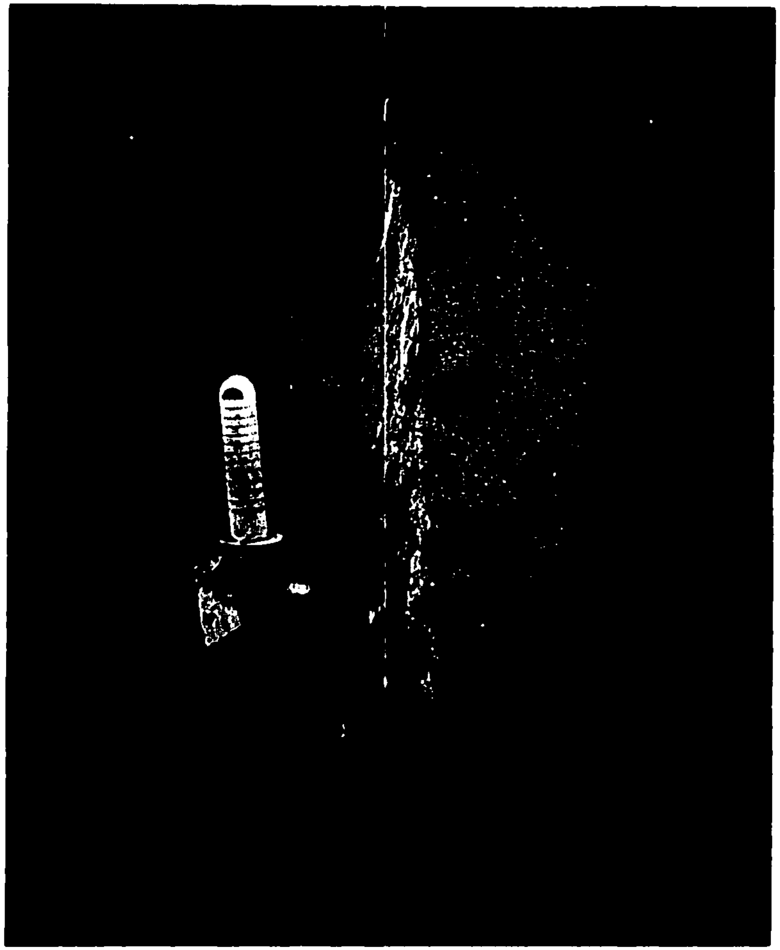


Figure 7.2 Near-vertical vein of calcium carbonate in road in cut soil exposure (CP309-1)

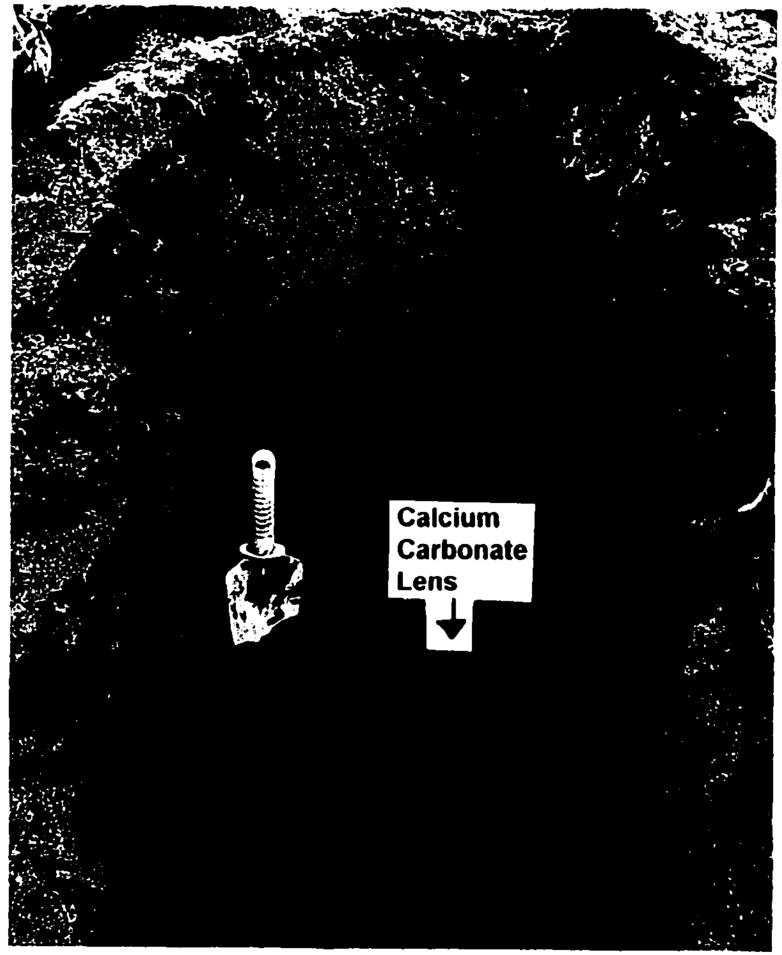


Figure 7.3 Subhorizontal layer of calcium carbonate in test pit at Slide 66044:01

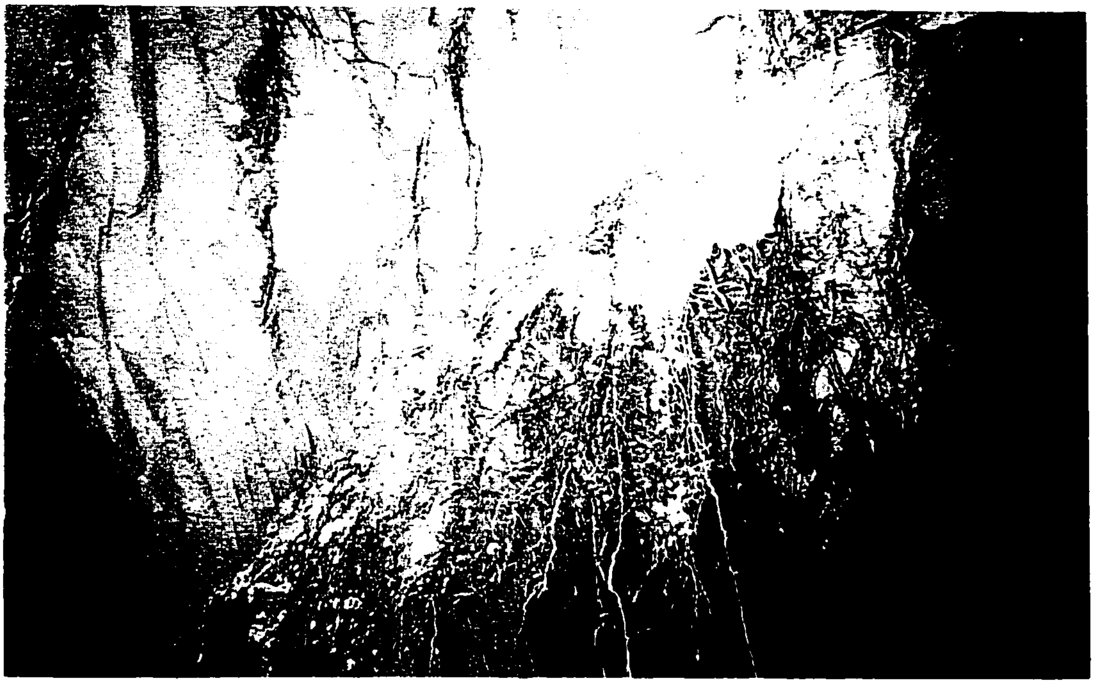


Figure 7.4 Calcium carbonate accumulations on roots in road cut exposure

Figure 7.5 Lobes of dry calcium carbonate-rich soil on rupture surface at Slide 65328:01

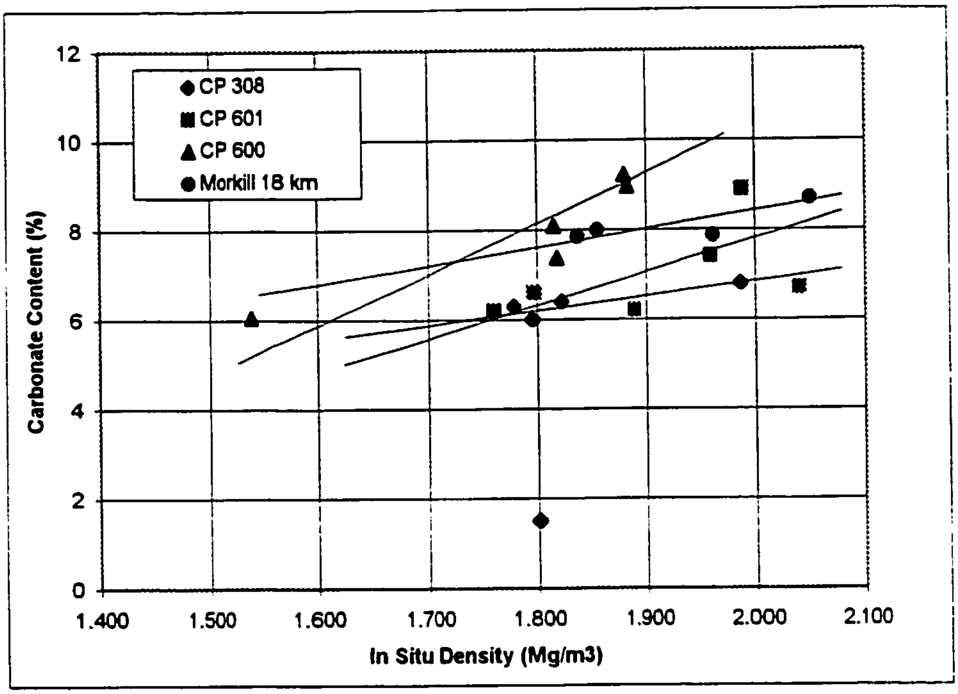


Figure 7.6 Lake A,B,C,E: Density vs. Carbonate Content (Soil Type: ML)

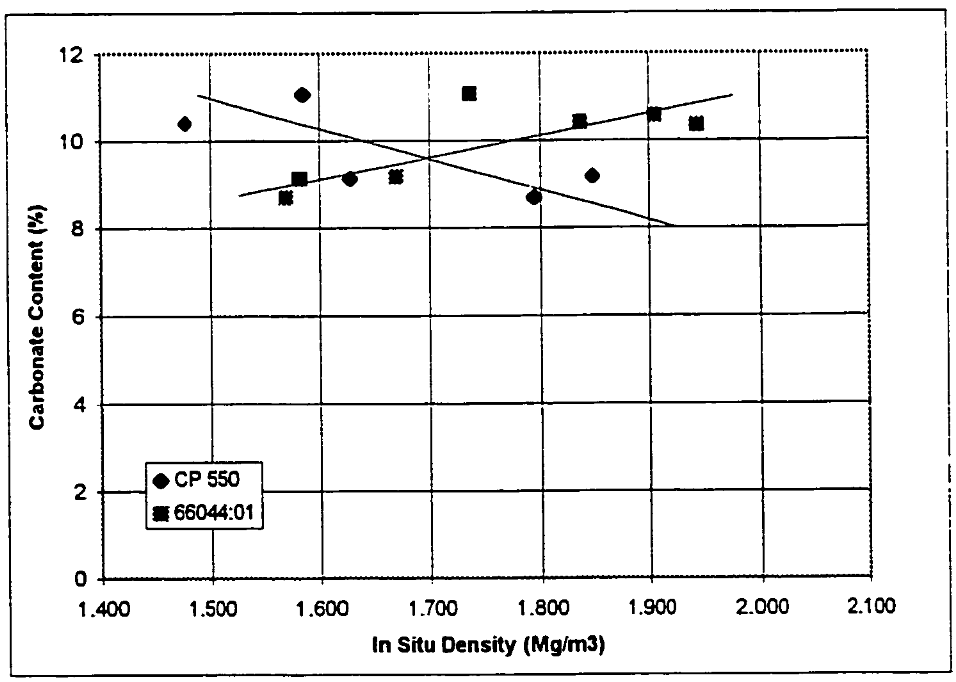


Figure 7.7 Lake A,B.D.E: Density vs. carbonate content (Soil Type: SP-SM)

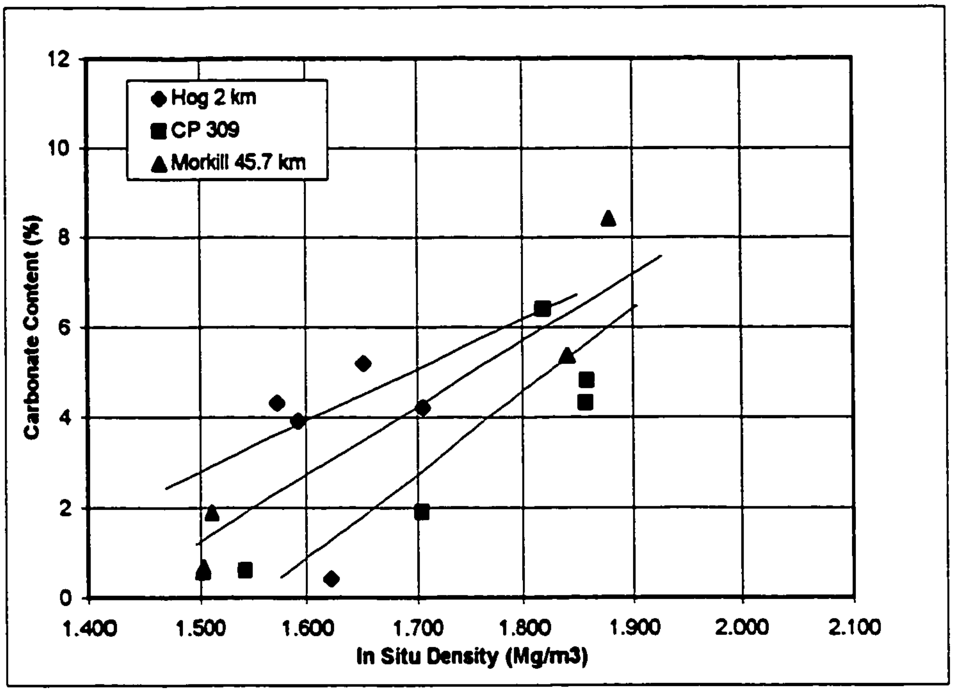


Figure 7.8 Lake C: Density vs. carbonate content

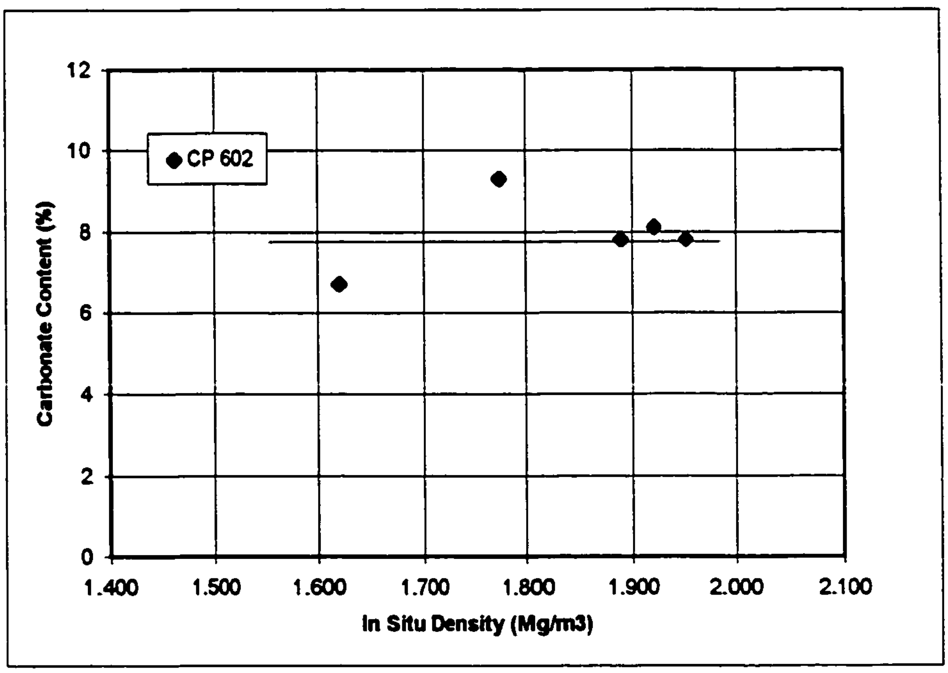


Figure 7.9 Lake F: Density vs. carbonate content

of the soils. The lower densities at the surface correspond to the mechanical weathering of the surficial soils.

7.4 Erosion

One of the most evident slope processes in the Morkill River valley, from a sediment delivery standpoint, is erosion, both surficial and internal.

The majority of landslides in the Morkill River valley have been initiated as shallow translational earth slides, incorporating the rootmat and top 15-30 cm of soil. The exposed silty soils are highly susceptible to erosion due to their relatively small grain size and poor cohesion.

Surficial erosion, such as shown in Figures 7.10 and 7.11 is common in exposed soil slope faces in the Morkill River valley. The upper 0.4 m of soil is often broken down and loose due to frost action and chemical weathering and is therefore highly susceptible to erosion by running water.

Internal erosion (piping) is also evident in the Morkill River valley. The natural varves in the lake sediments lead to preferential subsurface flow along higher permeability layers. During periods of high runoff, flow velocities in these layers are sufficient to transport particles of soil. The photos in Figures 7.12 and 7.13 show the characteristic holes at the surface of a slope and sediment fans associated with internal erosion.

Figure 7.10 Erosion in silty soils in road cut at Morkill 47 km

Figure 7.11 Erosion of exposed sandy silt soils at Morkill 26.5 km

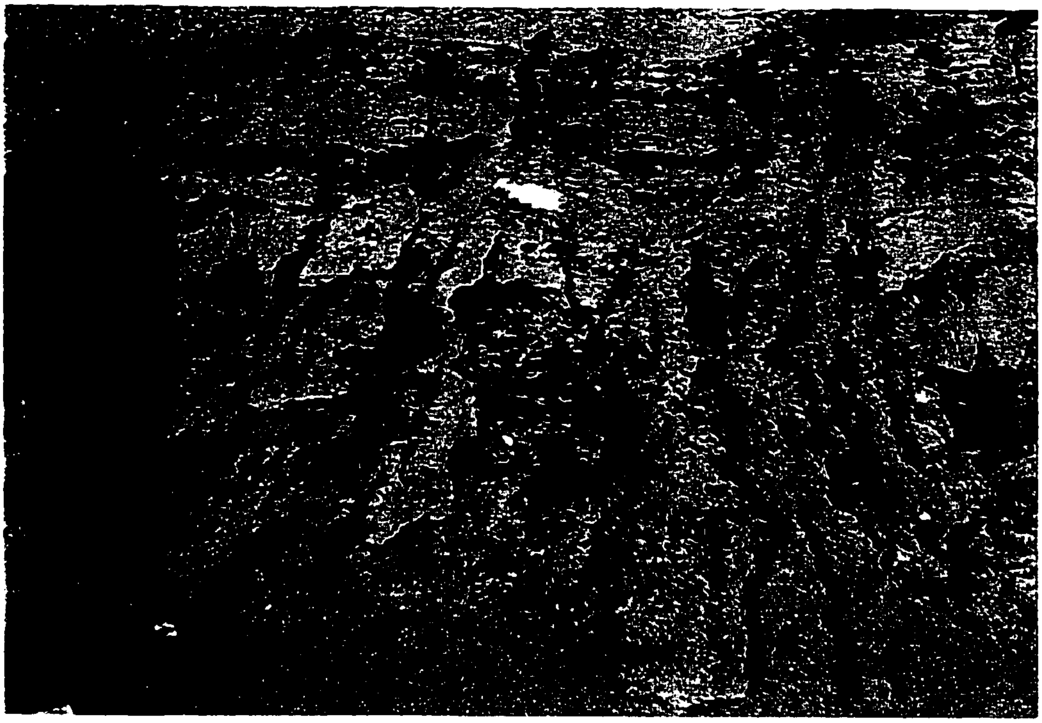


Figure 7.12 Small pipes formed in a road cut in coarse layers from internal erosion at Morkill 45 km

Figure 7.13 Fans of transported silty removed from road cut by internal erosion (CP340 Road)

7.5 Landslide Types and Processes in the Morkill River Valley

During the field mapping program in the Morkill River valley, I visited and investigated 21 landslides. The following sub-sections outline the types of landslides in the Morkill and the postulated mechanisms for each type.

A breakdown of my observations taken at the landslide locations, as well as the landslides that I inventoried during the office study (Chapter 3), is shown in Appendix A. The locations of the landslides are shown on the airphoto overlays in Appendix B.

7.5.1 Lakes A,B,D,E

During the field investigation I visited and investigated 10 landslides and 71 road cut exposures in the silty lake sediments of Lakes A,B,D, and E. These soils consist of varves of silt, fine sand and clayey silt. The lateral and vertical distribution of the sediments is presented on Figure 4.1 and described in Section 4.6.

Landslides in the soils consist of composite earth slide-earth flows. Landslides are initiated by shallow earth slides that encompass the upper 0.3 to 0.5 metres of rootmat and soil, followed by continuing retrogression of the rupture surface. The subsequent landslides occur in the form of composite slides and flows of the silty soils. Descriptions of the landslides in sediments of Lakes A,B,D,E are provided in the landslide inventory tables in Appendix A.

Based on my visual observations and slope measurements in the field mapping program (Chapter 4), natural slope angles adjacent to landslides and in road cut exposures in Lakes A,B,D,E range from 31 to 60°. In the landslides investigated, the slopes of the surface of rupture in the silty soils ranged from 35 to 60°. the variation in rupture surface orientation depended on the grain size, initial calcium carbonate content, time of exposure and corresponding degree of weathering.

The different types and mechanics of landslides in the silty soils of the Morkill River valley are discussed in the following paragraphs.

Earth Slides

Cruden and Varnes (1996) classified an earth slide as a downslope movement of soil mass occurring dominantly on surfaces of rupture or on relatively thin zones of intense shear strain. Movement does not initially occur simultaneously over the whole of what eventually becomes the surface of rupture; the volume of displacing material enlarges from an area of local failure.

The earth slides in the lacustrine sediments of the Morkill River valley are similar to what were termed translational earth slides by Cruden and Varnes (1996). These landslides have rupture surfaces ranging from 1 to 4 metres in depth with a range in width of 12 to 150 metres. The apparent depth of the rupture surfaces does not represent the depth of the rupture surface of the initial earth slide in most cases. Subsequent sliding and flowing caused the rupture surfaces to expand and retrogress.

The initiation of earth slides in the Morkill River valley silty lake sediments is postulated to be as a result of the gradual breakdown of the soil. The breakdown of the soil structure by mechanical processes in the zone of frost penetration, the active layer, combined with the dissolution and leaching of calcite cement reduces the overall shear strength over time. The strength is decreased to a point that the upper layer of soil is at limiting equilibrium and is held together by the rootmat at the surface. Once the rootmat is disturbed by nature or human activity, the upper soil and vegetation layer can be expected to slide in area where slope angles exceed 30 °. Examples of earth slides in the silty soils are 66044:03 (Figure 7.19), 66044:01(Figure 7.17), 65235:06(Figure 7.15) and the road cut at kilometre 2.8 of the Hellroaring FSR (Figure 7.14). Slides 66044:03 and 65235:06 are examples of large, natural, gully shaped slides found in the Morkill River valley.

Once the soils are exposed, the loss of the insulating vegetative mat allows for deeper frost penetration and disturbance, thus accelerating the degradation of soils. As described in Section 7.2, frost heave has a significant effect on the highly frost- susceptible silty soils.

The exposed soils are also susceptible to flow during the spring once the shear strength has been reduced sufficiently. Earth flows are described in the following section.

Earth Flows

Flows are defined by Cruden and Varnes (1989) as spatially continuous movement in which surfaces of shear are short-lived, closely spaced, and usually not preserved. The distribution of velocities in the displacing mass resembles that in a viscous fluid. When defining earth flows in thawing material, McRoberts and Morgenstern (1974) used the term skin flow to describe a rapid to very rapid slope movement in which a thin layer, or skin of thawed soil and vegetation flows or slides over the permafrost table.

The mechanics of earth flows in the Morkill River valley may follow Cruden and Varnes (1996, p. 66) description:

"Seasonal thaw layers, or active layers, up to a metre or so in thickness may contain water originally drawn to the freezing front where it formed segregated ice. Melting of this ice may generate artesian porewater pressures that greatly reduce the resistance of the active layer to movement."

During my field investigation, I noted layering developed parallel to the slope in the profiles in Lakes A,B.D.E. This layering was indicative of expansion and contraction of the soil matrix due to ice lens formation and frost heave. An example of this is shown in Figure 7.1. The melting of this ice led to excess pore pressures and a decrease in shear strength as described above. This process was discussed in Section 7.2.1.

Figure 7.14 Earth slide in silty soils on the Hellroaring Road at 2.8 km

Figure 7.15 Gully shaped rupture surface in earth slide (65235:06)

In the Morkill River valley, these earth flows appear to be initiated after vegetative cover is removed by initial shallow earth slides. The initial slide is normally followed by increased erosion and possible failure due to saturation of soil under the snow pack in spring. Similar slope processes are described for the loess deposits in Eastern Washington, USA, by Higgins and Modeer (1996). The similarities can be accounted for by the open soil structure created in the Morkill Silts by frost action and by the subsequent removal of calcite cementation. This open structure is also characteristic of the metastable loess deposits. Figure 7.16 compares the grain size ranges for the Morkill River silts and those outlined by Higgins (1995) for eastern Washington loess. As is shown in the plots, the grain size ranges for these soils is similar.

Evidence of successive annual or semi-annual flow events was noted in the Morkill River valley. In landslide 66044:03 (Site CP550, Figure 7.19), the landslide appears to have initiated as an earth slide followed by earth flows in subsequent years. The flow deposit shown in Figure 7.20 has a lateral extent of 40 metres from the toe of the slope with an average thickness of 0.3 m. Evidence of soil on small trees in the area, Figure 7.21, indicated that when the soil flowed, it reached levels up to 0.3 metres above the present levels without destroying the vegetation. This indicates a moderate to slow flow rate.

Evidence of seasonal flow due to frost creep is shown in Slide 66044:01 (Figure 7.17). In Figure 7.17 lobate flow features are evident, indicative of seasonal flow of the surficial soils. The photo is taken in the late spring of 1997. Figure 7.17 shows a close up of the effective depth of seasonal flow at this site.

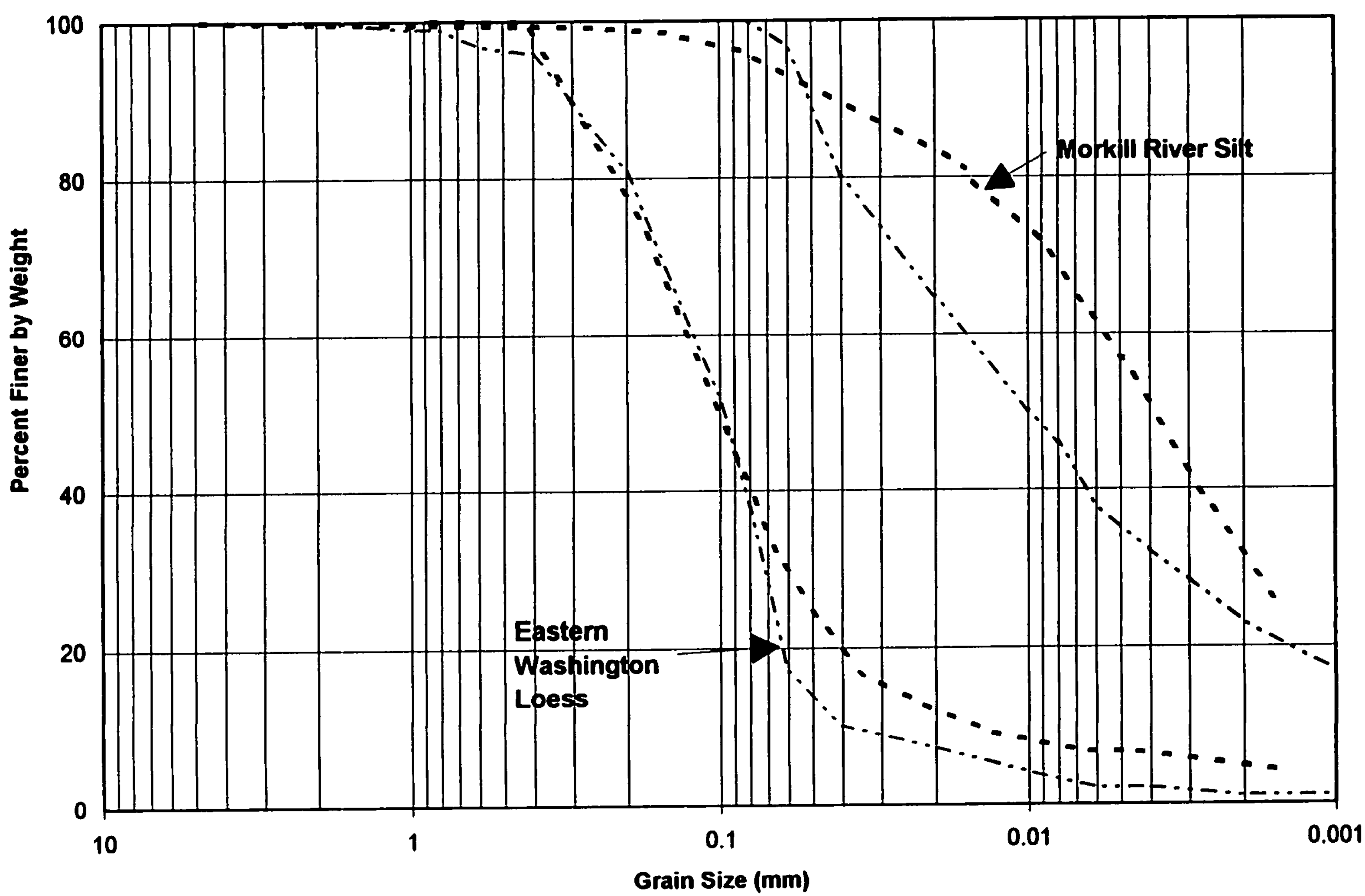
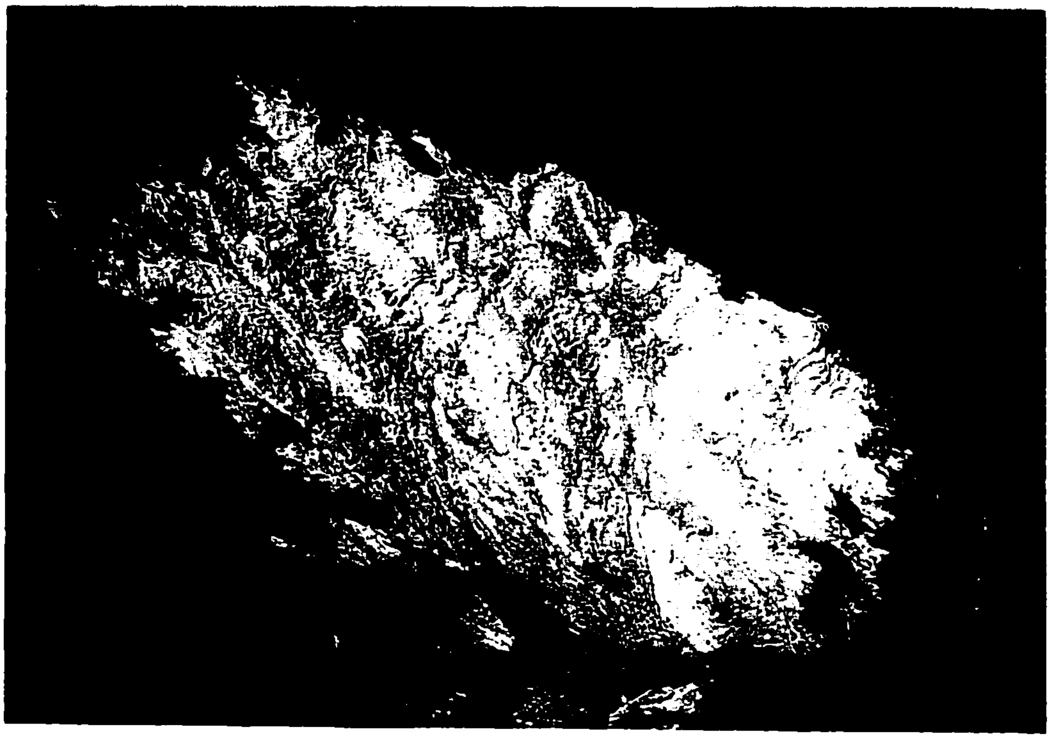


Figure 7.16 Comparison of grain size ranges for Morkill River silt and Eastern Washington loess (after Higgins and Modeer, 1996)



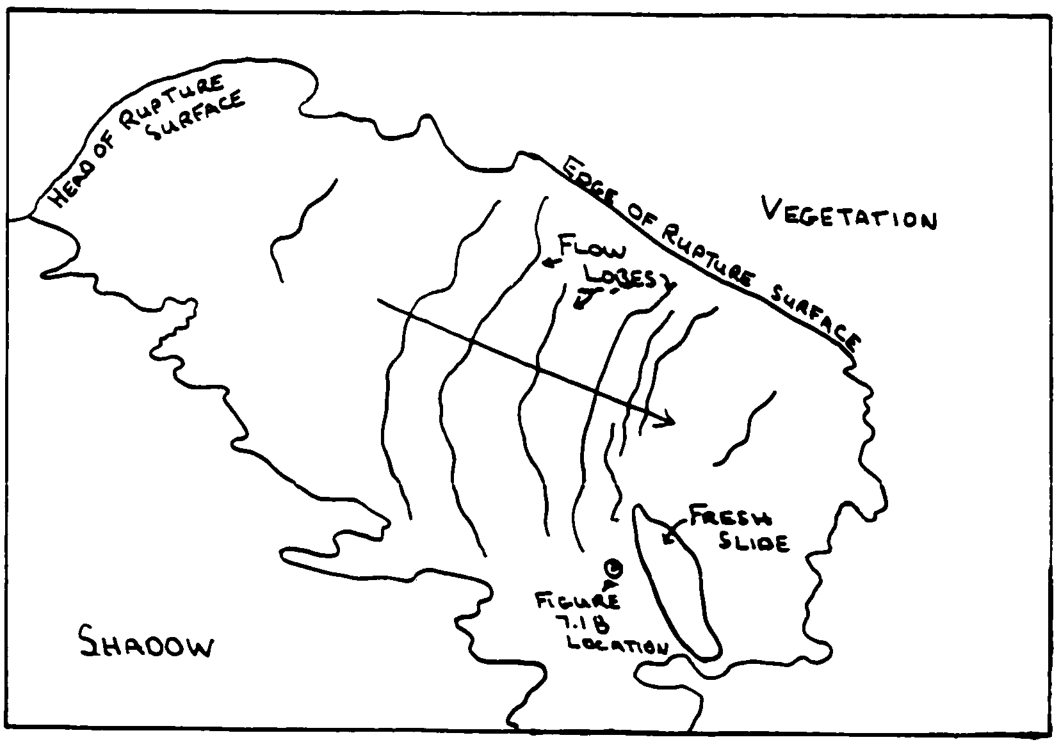


Figure 7.17 Slide 66044:01. Photo and overlay showing lobate flow features in large gully shaped composite earth slide-earth flow

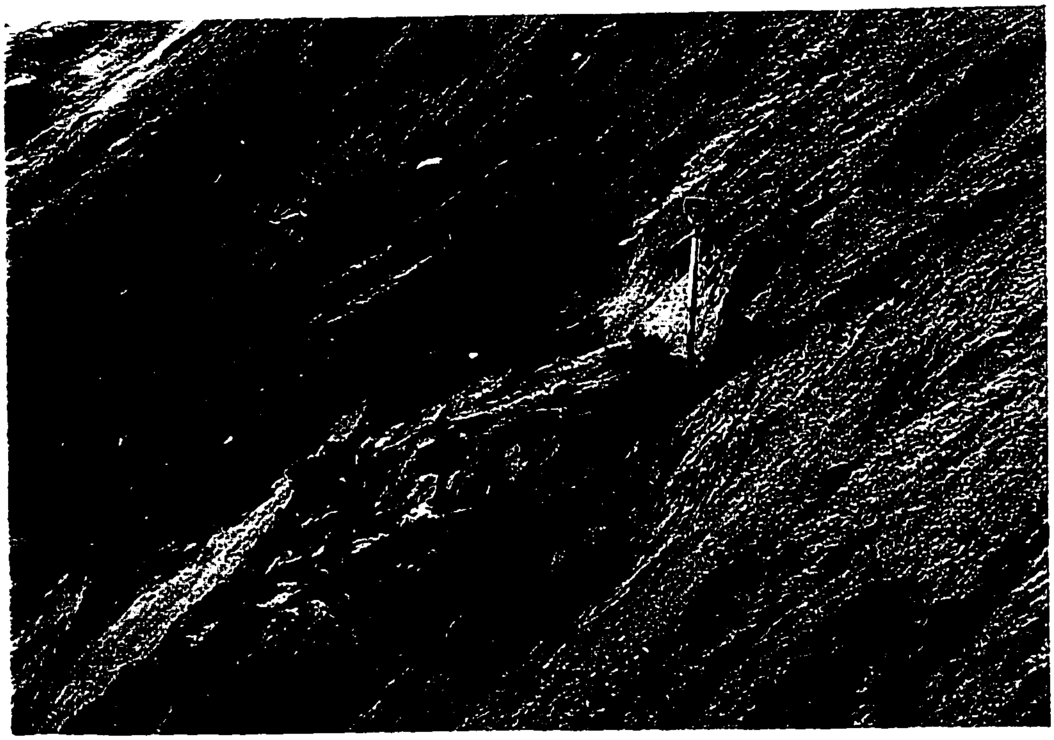


Figure 7.18 (Above) Slide 66044:01. Approximate depth of rupture surface for slide shown in Figure 7.16

Figure 7.19 (Left) Slide 66044:03. (CP 550-1) Composite earth-slide earth flow in harvested cut block

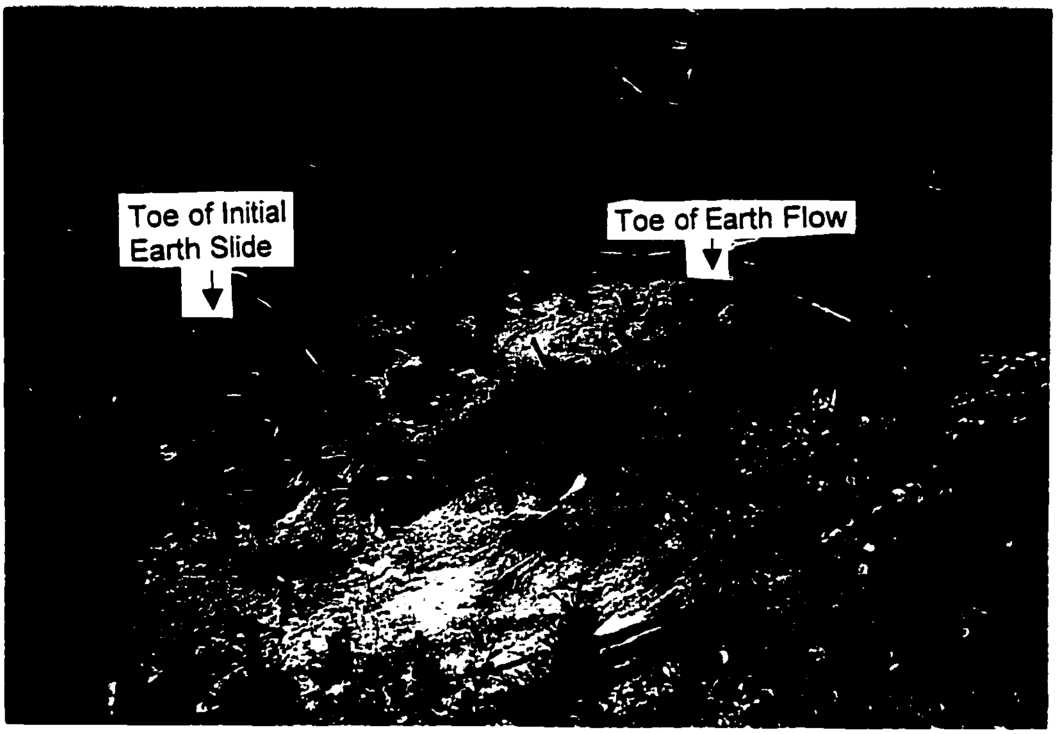


Figure 7.20 Slide 66044:03. View from head of rupture surface showing path of initial accumulated mass and subsequent earth flow

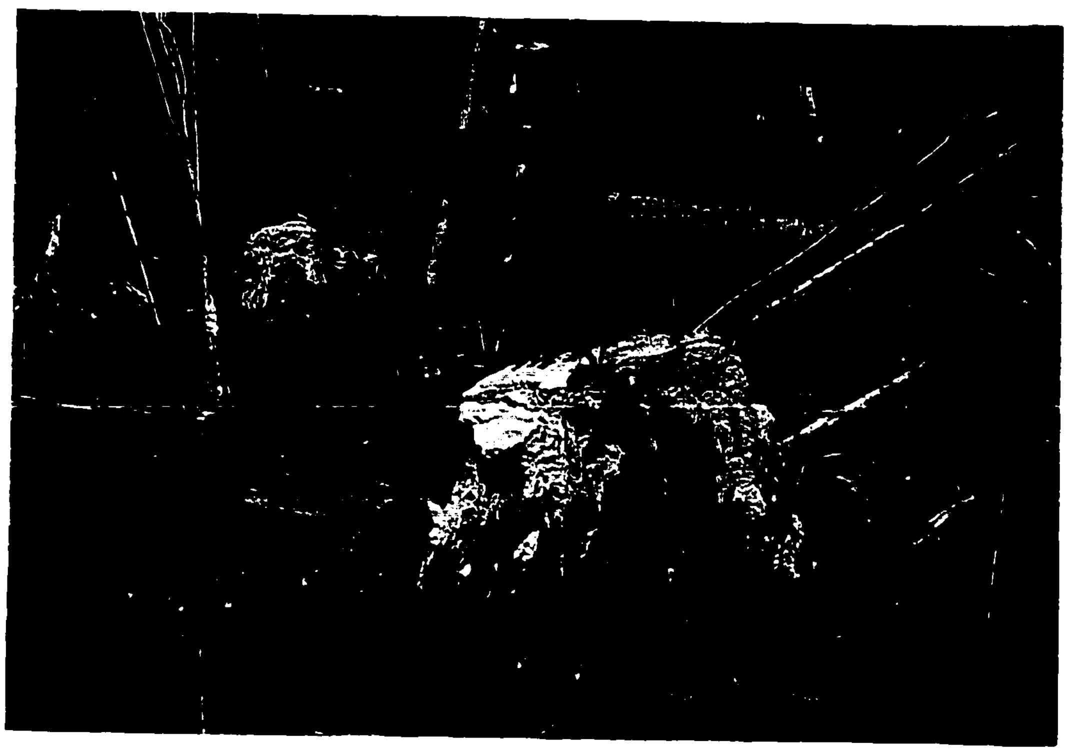


Figure 7.21 Slide 66044:03. Soil on young spruce trees is indicative of recent earth flow activity

In landslides 66044:01, 02 and 04, flows from the three areas have been channeled into a main gully and the flowing material directed onto a flat plain adjacent to the Morkill FSR at 13 Kilometre. The accumulated soil mass extends approximately 700 metres and is approximately 200 metres wide and over 1.2 metres in depth. In order to further explore the frequency of flow events, I excavated test pits into the displaced mass. I found evidence of organic debris (leaves) separating layers of soil 0.2 to 0.3 metres thick indicating that the material has been deposited by separate events in different years.

7.5.2 Lake C (Sand)

I visited a total of 11 landslides and 28 soil exposures in the sandy soils of Lake C. Landslides in the sandy soils of Lake C consist of primarily shallow, translational earth slides. Natural slope angles located adjacent to the slide areas ranged from 35° to 44° with rupture surfaces in the landslides ranging from 37° to 70°. The rupture surface of 70° was located in a relatively fresh exposure in a landslide (65243:03, Figure 7.22) that had occurred within the field season, in late spring 1997. Thus, it had not yet been exposed to freeze and thaw or chemical weathering.

The contribution of thaw weakening and frost heave is expected to differ in sandy soils and silts. As the freezing front progresses in the sandy soils, there is a downward expulsion of water forward of the freezing front, thus there is no ice lens formation. In natural soils, siltier varves of soil would be expected to retard the downward flow and water either freezes at these layers and expands, or is diverted along the lower permeability layers. Both processes enhance the loss of shear strength.

The most likely contributor to instability in the sandy soils is the dissolution and leaching of calcite, as discussed in Section 7.3.1. The higher permeability sand facilitates water flow and allows it to wash calcite out of the soil matrix more readily. Figures 7.22 and 7.23 show typical earth slides in the sandy soil of Lake C. The rupture surfaces in landslides in these sediments typically ranged in depth from 1.0 to 1.5 metres. The landslide in Figure 7.22. (65243:03) was assisted by the removal of toe material during road construction and subsequent excavation during seasonal ditch cleaning.

7.5.3 Lake F (Clay)

I visited 6 road cut exposures in Lake F, located between 47 km of the Morkill FSR and the termination of the road at 50 km. The limited area of lake sediments exposed, limited the number of sites and no large landslides were noted. Slope instability consisted of the gradual deterioration and erosion of the exposed soil due to frost action.

Field observations in a road cut exposure at the eastern most edge of CP 602 indicated distinct layering forming parallel to the slope surface due to frost heaving. The soils at the surface are blocky and disaggregated due to the frost action. The blocky nature of the soil is indicative of reticular ice formation during freezing. For this process, water migrates to the edges of soil peds and forms ice, thus separating the soil peds upon expansion of the ice.

Laboratory testing on a samples from CP 602, (Figure 6.4) shows a decrease of over 40 percent in unconfined compressive strength due to a single cycle of freeze and thaw. Visual observations of samples subjected to repeated freeze and thaw shows a significant breakdown of the soil structure and ice lens formation.

Figure 7.22 Slide 65243:03.(Morkill 45.7 km) Earth slide in sandy soils adjacent to road

Figure 7.23 Slide 65237:03.(Morkill 31.5 km) Earth slide in sandy soil below an abandoned cutting permit access road

7.6 *Conclusions*

The landslides in the Morkill River valley predominantly consist of shallow composite earth slide-earth flows in the weakly cemented lacustrine sediments. These landslides exhibit similar characteristics to the landslides in thawing permafrost of the Canadian Arctic permafrost (McRoberts and Morgenstern, 1973) and in loess deposits of Eastern Washington, USA (Higgins and Modeer, 1996).

The mechanism for instability in the stiff Morkill River lake sediments is the process of softening as a result of mechanical and chemical weathering processes. The first clear explanation of softening was put forward by Terzaghi (1936). He observed that fissures remain essentially closed as long as the clay is in its natural state. Following a cut, the clay expands and some fissures open. Water infiltrates these openings preferentially and the faces of the fissures swell, thereby weakening the clay mass. The process continues with time and may lead eventually to failure of the slope (Morgenstern, 1990). Weathering contributes to softening by causing the physical breakdown of the soil mass (Morgenstern, 1990).

The processes of frost action and leaching have differing effects on the soils depending on their grain size.

In the sandy soils of lake C, dissolution and leaching of calcite is expected to be the dominant weathering mechanism because of the relatively high permeability of the soil. As seen in the carbonate vs. density plots in Figures 7.6 - 7.9 and in the density profiles, Figures 5.2 a-j, there is a relatively steep relation between the amount of carbonate present and the density measured in the field in the sandy sediments. This is further substantiated by the observations of landslides in the field. The largest landslides associated with road construction, 65237:03 and 65243:03, in the Morkill River valley were associated with the sandy lake sediments. Landslides in these soils are predominantly classed as shallow earth slides. These slides are typically 1 to 1.5 metres in thickness with widths ranging from 20 to 75 metres in the Morkill River Valley

In the silty soils of Lakes A,B,D,E, I consider that frost action is the initial dominating weathering process followed by dissolution and leaching. Once the calcite bonds have been broken due to the nine percent volume expansion upon freezing, the calcite is more readily leached out of the soil structure. The loss of strength noted in the laboratory freeze/thaw testing coupled with the profiles taken in the field indicate that there is significant effect of frost action followed by slower removal of the calcite, when compared to the sandier soils. Landslides in these soils consisted predominantly of shallow composite earth slide-earth flow events. It is postulated that initial slides, incorporating the rootmat and upper 0.3 metres of soil initiated the landsliding followed by seasonal flowing and erosion of the exposed slope face in the spring.

In the clayey soils of Lake F, landslides were not noted in the limited number of exposures that I investigated. The soil profile taken at CP602 indicated a very gradual decrease in density and carbonate with depth as shown in the profile, Figure 5.2.j, and the relatively flat carbonate vs. density plot (Figure 7.9). In these soils, the clay minerals are considered to be the dominant cementing agent and the low permeability of the material does not favour percolation of groundwater and leaching of carbonates. These soils are susceptible to gradual breakdown of the soil structure due to frost action.

Chapter 8: Application to Terrain Studies

8.1 Introduction

Objective 4 of this study is to provide a methodology for developing a probabilistic model for assessing relative frequencies of landslides for terrain stability mapping, detailed on site surveys and terrain attribute studies that incorporates soils strength properties and contributing factors, both human and natural. This chapter summarizes the characteristics of the lake deposits as well as addressing the performance of cuts in the soils of the Morkill River valley.

8.2 Performance of Road Cut Exposures

In investigating landslides in the Morkill River valley, I completed an inventory of 102 road cut exposures along cutting permit roads that were accessible during the summer of 1997. The roads visited were for cutting permits CP 501, CP 303, CP 308, CP 309, CP 340, CP 330, CP 600, and CP 604. Results of this inventory are represented in the following sections.

8.2.1 Lakes A,B,D,E

I visited a total of 71 road cut exposures and 10 landslides in the silty sediments of Morkill River valley. A histogram showing the distribution of slope angles in these sediments is shown in Figure 8.1. I have divided each bar in the histogram into 2 sections: slopes that were performing acceptably (showing minimal erosion or instability) and slopes that were not performing acceptably. Specific examples of unacceptably performing slopes that I visited during the field landslide inventory were 66044:03 in Lake A; 65235:11, 66044:01, 66044:02, 66044:04, 65235:09, 65235:06 in Lake B; 65239:01, 65239:02 in Lake D. Observations of slopes in the field landslide inventory are given in the landslide inventory tables in Appendix A with corresponding locations provided on the air photo overlays in Appendix B. The slopes shown in Figures 7.10 through 7.15 are examples of slopes in Lakes A,B,D,E that are not performing acceptably.

As can be seen from Figure 8.1, the range in slope angles is from 25° to 60 ° with the largest concentration ranging from 41° to 45 °. Slopes that I noted as prone to erosion and instability are indicated to occur in the range of 31° to 45 ° in the slopes visited during my field investigation.

Based on the above findings and the instability mechanisms described in Chapter 7, it is apparent that cuts with slope angles greater than 30 ° in the silty lake sediments have a higher probability of eroding than those with angles less than 30°. Thirty degrees may be a threshold slope angle above which unacceptable performance may occur. There is expected to be some variation in this slope angle threshold based on initial calcium carbonate content, time of exposure and degree of weathering. The longer the period of time for which the soils are exposed to surface water and frost action, the deeper the degradation of the soil by weathering, as discussed in Chapter 7 and the lower the slope angle threshold.

As demonstrated in Figure 8.1, 44 of the slopes were found to be standing above the threshold slope angle of 30°, of which 38 of these were performing acceptably. One possibility of why acceptable slope performance occurs above the threshold slope angle for the silty soils is described below.

One possibility of why some slopes performed acceptably at angles over 30° is that their length of exposure to weathering was so short that a significant amount of calcite remained in the soil structure to hold the slope its friction angle. As discussed in Chapter 7, the grain size distributions of the undisturbed silts are such that leaching is much slower than in sands, until frost action and ice lens formation has broken down the soil structure. The extra time taken for the calcite cement to be removed from the structure may account for the short to midterm performance of slopes noted during the field program. This hypothesis suggests performance problems in additional cuts later.

Based on the knowledge that the undisturbed silty soils have high shear strengths and have similar grain size characteristics to the loess deposits of Eastern Washington (Figure 7.16), slopes in the silty sediments of the Morkill River valley might be designed using near-vertical cuts as used in loess deposits in the United States as discussed by Higgins and Modeer (1996). However, near-vertical cuts are only effective in dry, arid climates. The high precipitation and the extreme climatic fluctuations in the Morkill River will reduce the strength of the silty soils sufficiently that they will not stand in slopes over 30° in the long term. Once the vegetative mat is removed from the highly frost susceptible soils, deeper frost penetration and subsequent ice lens formation will lead to a loss of shear strength of the soils and ultimately slope failure as described in Section 7.2.

The freeze thaw tests shown in Figure 6.5 indicated that values of cohesion of 60 kPa and 35 kPa were available in the silty and silty clay soils, respectively, after one cycle of freeze and thaw. In order to evaluate the effects of freeze and thaw on the stability of slopes in the fine grained sediments of the Morkill River valley, an infinite slope analysis was undertaken. The analysis was undertaken as shown in Duncan (1996, p.351) and assumed a layer with thickness of 1 metre with a friction angle of 30°. Due to the enhanced permeability after a cycle of freeze thaw, pore pressures are assumed to be dissipated and the fully drained condition is modeled.

The infinite slope analysis demonstrates that values of cohesion of less than 10 kPa are required to maintain a slope of 60° at a factor of safety of 1.0 under short term conditions. As this value is less than the values of cohesion available after one cycle of freeze and thaw, it is considered that the slopes in the silty and silty clay soils require several cycles of freeze and thaw and prolonged exposure to weathering to soften the soil and lower the cohesion to a point at which limiting equilibrium is achieved.

8.2.2 Lake C

I visited a total of 28 road cut exposures and 11 landslides in the sandy sediments of Morkill River valley. A histogram showing the distribution of slope angles in these sediments is shown in Figure 8.2. As above, I have divided that each bar in the histogram into 2 sections: slopes that were performing acceptably (e.g. minimal erosion or instability) and slopes that were not performing acceptably. Specific examples of unacceptably performing slopes in the sandy sediments of Lake C that I visited during the landslide inventory are 65235:02, 65235:09, 65235:07, 65235:12, 65237:02, 65237:03, 56237:04, 65237:05, 65237:06, 65243:03, 65243:04. Observations for slopes observed during the field landslide inventory are given in the landslide inventory tables in Appendix A with corresponding locations provided on the air photo overlays in Appendix B. The slopes shown in Figures 7.22 and 7.23 are examples of unacceptable performance in slopes in the sandy soils.

As can be seen from Figure 8.2, the range in acceptable slope angles is from 20° to 50 °with the largest concentration from 25° to 35° degrees. This range reaches what is considered to be the friction angles for sand (Lambe and Whitman, 1969, Table 11.2). Slopes that I noted were prone to erosion and instability are indicated to occur in the range of 31° to 45° in the slopes visited during my field investigation.

Based on the above findings and the instability mechanisms described in Chapter 7, it is apparent that cuts with slope angles greater than 30° have a higher probability of eroding and failing than those with angles less than 30° in the sandy lake sediments. For cohesionless sandy soils, drained friction angles of 30° to 39° are typical (Lambe and Whitman, 1969, Table 11.2) and therefore the soils are considered to be active in a normal fashion. Of course, there is expected to be an increase in stable slope angle with calcium carbonate content. With exposures, seepage and runoff dissolves and leaches calcite from the soil structure, breaking down the soil and making it more susceptible to erosion. The slopes with high initial calcium carbonate content and little exposure to

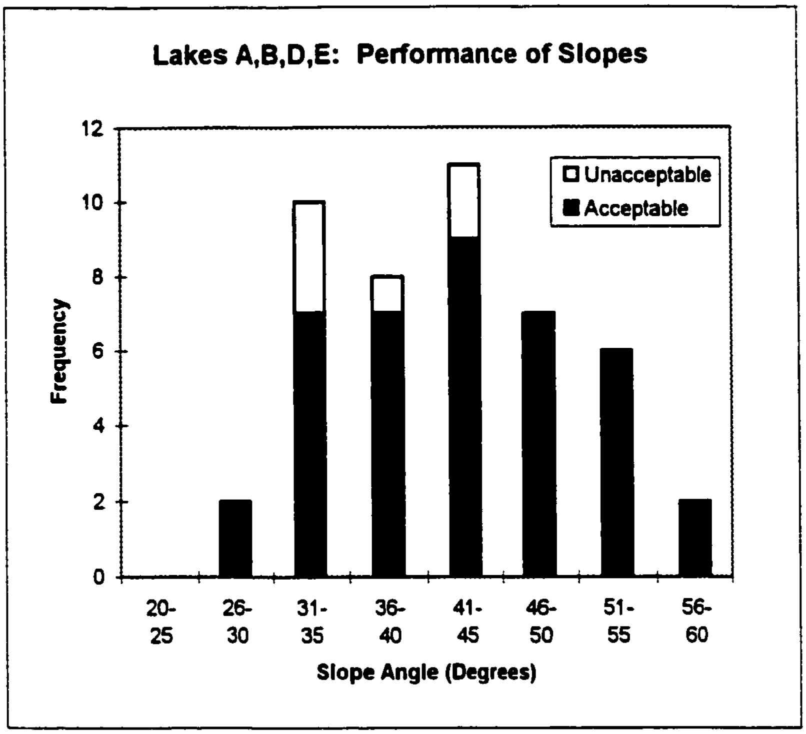


Figure 8.1 Slope angle frequencies for Lakes A,B,D,E

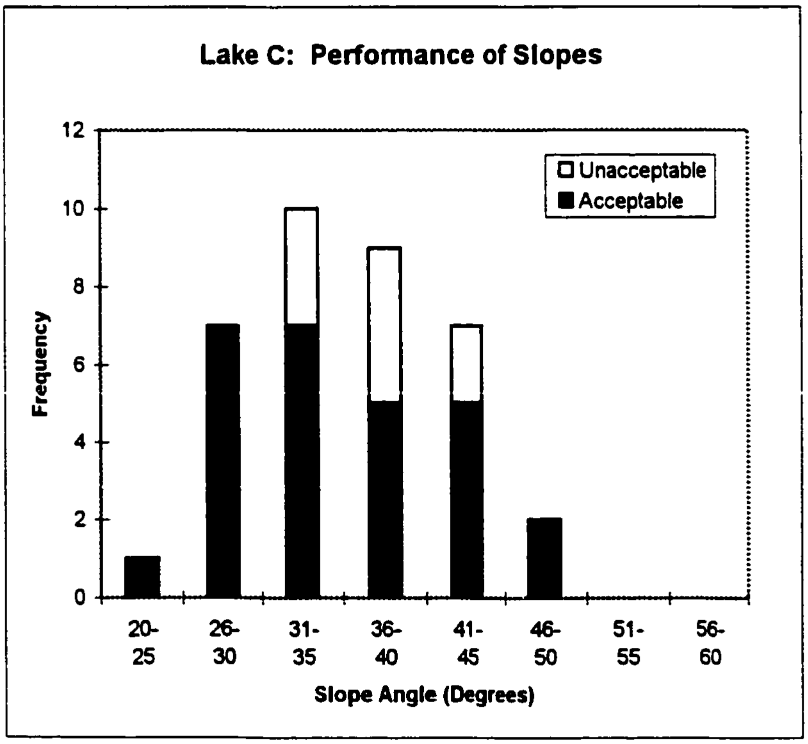


Figure 8.2 Slope angle frequencies for Lake C

weathering might stand at angles of up to 50° prior to a seasonal cycle of freeze and thaw, as shown in Figure 8.2.

8.2.3 Lake F

As there were only exposures of the clayey sediments of Lake F from 47 to 50 kilometres of the Morkill Forest Service Road, only 5 road cut exposures were investigated. This area is located at the easternmost extent of the Morkill Forest Service Road, as shown on the overlay for airphoto BCB91065 No. 242 in Appendix B. This small number of exposures does not allow for a reliable compilation such as those presented in Figures 8.1 and 8.2 for the other lakes. Based my observations in the soils of Lake F, soils in road cut exposures were not performing well with respect to erosion and stability. The cut slope at the eastern extent of CP 602-2 was cut at over 35 ° and the top 0.5 metres of soil has been broken down by frost action and had moved downslope, indicating that this cut was oversteepened. Based on Terzaghi et al. (1996, Figure 19.7) typical friction angles for stiff clays with plasticity indices between 5 % and 20% are from 25° to 35 °. It is therefore considered that, in the stiff silty clays of Lake F, slope angles below 25 ° could be expected to perform acceptably.

8.3 Evaluation Techniques

Taking observations of slope angles and the performance of road cuts in developing areas can be a valuable tool in developing models for watersheds to be used in reconnaissance planning and detailed on-site assessments. In areas where access is made by foot or helicopter, observations of slope angles in areas of slope instability and stable ground provide a useful way in which to gain further insight and organize data from large areas with similar geology. As can be appreciated, each set of observations will be limited in application to within an area in which the geology and depositional environments are similar. By making the observations of a sufficient number of slope angles within terrain units, figures such as those represented in Figure 8.1 and 8.2 can be prepared using readily available spreadsheet programs. Threshold slope angles obtained from the histograms can then be used as an input parameter within terrain units to provide a preliminary zoning of hazards based on slope angles. This system highlights the ranges in slope angles that create landsliding and erosion hazards during resource extraction and development.

In this study, the threshold slope angles represented limits for surficial landsliding. As discussed in Section 8.2.1, the threshold angles apply only to the drained, cohesionless soils within the top 0.3 to 0.5 metres of the surface. These generalizations do not apply to deeper, unweathered sediments that act in an undrained manner, different from those outlined in Figure 8.1 and 8.2.

Although the slope angle is a useful input parameter, it requires an understanding of the geology and deposition of the sediment to which it is to be applied. From this study, sediments were divided into units with similar characteristics based on the field mapping program. This required observations of the elevations and spatial distribution along the valley and observations of the index properties of the soils. Zoning the sediments from Lakes A,B,D,E into one unit with similar characteristics greatly simplified the process of evaluating the problems and challenges associated with each unit. Without a clear understanding of the glacial geology and depositional environment, zoning of the sediments would have been much more difficult.

Undertaking this study in a phased approach, providing more detail at each stage, was an efficient method of collecting data to input into a probabilistic model for assessing relative frequencies of landslides. It further focuses the observations on site-specific areas by providing a plot of how a large number of representative slopes in similar soils and topographic regions acted and reacted to natural and human disturbance.

In using this method as a tool to aid in the planning of forestry activities and detailed terrain studies it is important to understand the limitations. Any correlations must take into account the geology and depositional environment. There will be differences in grain size and soil properties depending on the bedrock from which they were derived and the method of deposition. As well, when considering cementation in soils, the initial amount of carbonate cementation will vary within a terrain unit depending on the source of the carbonate and the degree of weathering. Whenever dealing with geology, it is important to understand that there are anomalies and that the only perfect model from interpreting the geologic history of an area is the area itself. All of these above are considerations when applying field investigation results in regional studies. The mechanics of landsliding should also be understood, as discussed previously in this section, if slopes are acting differently than expected.

8.4 Implications for Construction Techniques

With the knowledge of the threshold slope angles of 30° for the silty and sandy soils and 25° in the clayey soils, applications to road construction can be made.

Avoidance of cuts in slopes which are over 30° in the silts and sands and 25° in the clayey soils, wherever possible, is a prudent guideline when planning route alignments for road corridors. If slopes adjacent to roads are greater than the threshold slope angles then possible slope failures and subsequent sediment generation need to be considered if these slopes are disturbed.

Where cuts cannot be avoided, stabilization of oversteepened slopes by means of retaining structures, geosynthetics or vegetation is suggested if there is a possibility of sediment being routed into fish-bearing streams.

During my field investigation, I noted the use of retaining structures consisting of timber pile walls, gabion walls and tangent pile walls along the Morkill River and tributary valleys, which exhibited varying degrees of performance. Other, possibly more suitable, methods of slope stabilization are outlined in Holtz and Schuster (1996).

Gabion or rock walls, utilizing locally available materials, are a preferred stabilization technique in most cases based on the economics, availability of material and low stresses imposed on the structures due to the absence of deep seated sliding. The main design considerations in designing retaining structures in the weakly cemented soils are to provide resistance to sliding of the surficial soils above the cut slopes, provide a geofilter between the wall and backfill material to minimize the migration of fines and to provide a granular backfill or synthetic insulation behind the wall to retard the advance of frost into the undisturbed soils behind the wall to reduce softening.

Geosynthetic reinforcement in the form of reinforced soil structures or protective mats may also be considered. Geosynthetics in the form of strips or grids are typically used for reinforcement purposes. A detailed listing of the types and applications for geosynthetics is discussed by Koerner (1997) and Holtz et al (1997).

Vegetative matter is also utilized to protect slopes from rainsplash erosion, to increase the shear strength of the surficial soils by removing excess pore water by transpiration, and to provide insulation from frost action. A detailed listing of the types and applications of vegetation in slope stabilization is provided by Gray and Sotir (1996).

Detailed construction techniques are not outlined in this sections as each site should be considered separately in any design. Site conditions, economics and acceptable risk will govern the design for each individual site.

8.5 Conclusions

During the study of landslides in the Morkill River valley, I gathered observations of road cuts and natural landslides and represented the data in the histograms presented in Figures 8.1 and 8.2. These histograms demonstrated that slopes over 30° in both the silty and sandy lake sediments did not perform acceptably from a sedimentation and stability perspective. The minimal amount of exposures in the clayey sediments of Lake F did not allow for a reliable representation of the distributions of slope angles and relative frequencies but, based on the performance of the cuts inventoried and the plasticity of the soils, threshold slope angles of 25° should be used in the clayey soils.

The methodology used in the field program for gathering this information in the Morkill River valley could be applied to other terrain stability studies. By dividing areas into terrain units with similar geotechnical characteristics, observations of slope angles within these units can be represented in histograms of frequency vs. slope angle to provide an easy to manage graphical depiction of a large amount of data which can be utilized to make judgments and to highlight potential concerns during the planning of future activities. Knowledge of the limitations associated with the geology, soil properties and landslide mechanisms is essential in this application.

The knowledge of the threshold slope angles and soil properties can be applied to road construction techniques. Cuts should be avoided in slopes that exceed the threshold slope angles of 30° in the silty and sandy soils and 25° in the clayey soils. If cuts are to be made, suitable slope protection and stabilization in the form of retaining structures, vegetative material and/or geosynthetics will be required if sediment generation is of concern. Design of reinforcement or slope protection must be addressed on a site by site basis. Soil conditions, economics and acceptable risk will govern any design.

Chapter 9: Conclusions

9.1 Conclusions

Studies of the location and index properties of carbonate sediments in Western Canada , when compared to Ford's (1989, Fig. 6.4.3) map of the occurrence of soluble rock in Canada shows a direct correlation between the occurrence of soluble bedrock and carbonate sediments. This highlights the likelihood that recent sediments derived from the Canadian Rockies contain at least a small amount of cementation, carbonate or otherwise. The Morkill River valley is such an area (Chapter 3).

The Morkill River is located in the Rocky Mountains and is susceptible to extreme climatic variations. These conditions contribute to a moderate amount of chemical weathering and weak to moderate mechanical weathering of the sediments and bedrock in the area. The weathering of sediments and associated loss of strength appears to be a major contributor to slope instability in the area. An initial landslide inventory and site visit to the Morkill River watershed highlighted the high susceptibility of the lacustrine sediments in the area to landsliding and erosion (Chapter 3). Of the landslides inventoried, 131 of 159 are interpreted to occur in the lake sediments.

I undertook a detailed field mapping program in the Morkill River valley in the spring and summer of 1997 (Chapter 4). By following through the landslide inventory and subsequent surficial mapping, the properties and distribution of the sediments and their source materials in the Morkill River valley were observed.

From this study, I concluded that at least six lakes were present in the Morkill River valley during the complex stagnation and downwasting of valley glaciers in the Quaternary. At various times large blocks of ice and debris formed natural dams throughout the Morkill River and tributary valleys, producing large sediment traps . Shoreline elevations were noted at 840 m.a.s.l (Lake A), 900 m.a.s.l. (Lake B), 1020 m.a.s.l. (Lake C), 1120 m.a.s.l. (Lake D), 1260 m.a.s.l.

(Lake E) and 1000 m.a.s.l. (Lake F). The sediments in these lakes were generated from the local bedrock in the Morkill and tributary valleys with weakly cemented sediments in the valley most likely derived from the carbonate rich bedrock or till.

During the field program I undertook in situ testing of selected field exposures (Chapter 5). The main purpose of the in situ testing field program was to quantify the relative change in density with depth of the lacustrine sediments and also the corresponding change in carbonate content. The field estimation of carbonate content provided a relative scale during the field program that was backed up quantitatively using samples taken from the density testing program. The soils in the Morkill River valley were classified as weakly to moderately calcareous based on the criteria outlined. The in situ density tests yielded densities in the undisturbed sediments of up to 2.05 Mg/m^3.

Based on the field observations there appears to be a linear increase in in situ density with a corresponding increase in carbonate content (Chapter 6). In order to quantify the carbonate contents in the samples taken when obtaining the field profiles, I used a vacuum distillation/titration procedure to determine the carbonate content the lacustrine soils in the Morkill River valley. Carbonate contents of 5.2 to 11.1 % were obtained for unweathered samples. These maximum carbonate contents, along with the unconfined compression test results of the intact samples of approximately 250-270 kPa identify the soils tested as very stiff, non to weakly calcareous silts and muds (clay) according to Fookes' (1988) classification.

Scanning electron microscope (SEM) photographs of the lacustrine sediments, Figures 6.7 and 6.8, did not show any carbonate grains while electron diffraction analyses of soil grains in the photos indicated trace amounts of $CaCO_3$ in the soil matrix. These observations, coupled with the results of the carbonate content determination, support the view that there are carbonates located in the soil matrix as a cement, precipitated from local groundwater saturated with calcium carbonate derived from calcite rich bedrock or till in the Morkill watershed.

I undertook Atterberg limit tests and hydrometer tests in order to gather index data for use in the classification of the soil in the Morkill River by the Unified Soil Classification System. Based on this system, the soils in the Morkill River valley were predominantly sandy silts, silty sands and clayey silts, with poorly graded sands located at the Hog road, CP 550 and M45.7. The plasticity indices of the cohesive soils indicates that the silts and clayey silts are low plastic. Figures 6.1 and 6.2 provide graphical indications of the grains size analyses and Atterberg Limits, respectively.

Density results were obtained in the field using a rubber balloon apparatus (ASTM, 1997b) and in the laboratory using samples obtained from Shelby tubes and block samples obtained during the field program. In situ densities for the lacustrine sediments ranges from 1.77 Mg/m^3 to 2.20 Mg/m^3 with corresponding void ratios of 0.82 to 0.36. The lowest void ratio soils correspond to minimum reported values of void ratios for inorganic silts and silty sands and are therefore considered to be very dense.

Frost susceptibility of the lacustrine sediments was addressed using both the index properties of the soils and laboratory strength testing. Using the US Army Corps of Engineers (1965) classification criteria, coupled with Davila et al's (1993) correlations for segregation potential, the soils tested are considered to have a moderate to very high susceptibility to frost action and a low susceptibility to frost heave.

The laboratory testing for the effects of frost action on the soils consisted of unconfined compression tests conducted on samples from CP 601 and CP 601 that had been subjected to 0, 1, 2, 5 and 10 cycles of one-dimensional freeze and thaw. Samples exhibited a 50% decrease in strength after one cycle of freeze and thaw. Visual observations of the samples tested showed that the structure of the sandier sample, CP601, appeared well bonded after 10 cycles of freeze and thaw, while the structure of CP 602, a sample with 43 % clay size fraction, exhibited stratified ice formation and segregation after 10 cycles of freeze and thaw.

The landslides in the Morkill River valley predominantly consist of shallow composite earth slide-earth flows in the weakly cemented lacustrine sediments and were discussed in Chapter 7. These landslides exhibit similar characteristics to the landslides in thawing permafrost of the Canadian Arctic permafrost (McRoberts and Morgenstern, 1973) and in loess deposits of Eastern Washington, USA (Higgins and Modeer, 1996).

The mechanism for instability in the stiff Morkill River lake sediments is the process of softening as a result of mechanical and chemical weathering processes. Weathering contributes to softening by causing the physical breakdown of the soil mass (Morgenstern, 1990). The processes of frost action and leaching have differing effects on the soils depending on their grain size distributions.

In the sandy soils of Lake C, dissolution and leaching of calcite is expected to be the dominant weathering mechanism because of the relatively high permeability of the soil. As seen in the carbonate vs. density plots in Figures 7.5-7.7 and in the density profiles, Figures 5.2 a-j, there is positive correlation between the amount of carbonate present and the density measured in the field in the sandy sediments. This is further substantiated by the observations of landslides in the field. The largest landslides associated with road construction, 65237:03 and 65243:03, in the Morkill River valley were associated with the sandy lake sediments. Landslides in these soils are predominantly classed as shallow earth slides. These slides are typically 1 to 1.5 metres in thickness with widths ranging from 20 to 75 metres in the Morkill River valley

In the silty soils of Lakes A,B,D,E, I consider that frost action is the initial weathering process followed by dissolution and leaching. Once the calcite bonds have been broken due to the nine percent volume expansion upon freezing, the calcite is more readily leached out of the soil structure. The loss of strength noted in the laboratory freeze/thaw testing, coupled with the profiles taken in the field, indicate that there is significant effect of frost action followed by slower removal of the calcite, when compared to the sandier soils. Landslides in these soils consisted predominantly of shallow composite earth slide-earth flow events. It is postulated that slides, incorporating the rootmat and upper 0.3 metres of soil initiate the landsliding followed by flows and erosion of the exposed slope face in the spring

In the clayey soils of Lake F, landslides were not noted in the 5 exposures that I investigated. The soil profile taken at CP602 indicated a very gradual decrease in density and carbonate with depth, as shown in Figure 5.2.j, and the relatively flat carbonate vs. density plot (Figure 7.7). In these soils, the clay minerals are considered to be the dominant cementing agent and the low permeability of the material does not favour percolation of groundwater and leaching of carbonates. These soils are susceptible to gradual breakdown of the soil structure due to frost action.

During the study of landslides in the Morkill River valley, I gathered observations of road cuts and natural landslides and represented the data in the histograms presented in Figures 8.1 and 8.2 (Chapter 8). These histograms demonstrated that some slopes over 30° in both the silty and sandy lake sediments did not perform acceptably from a erosion and stability perspective. The minimal amount of exposures in the clayey sediments of Lake F did not allow for a reliable representation of the distributions of slope angles and relative frequencies.

The methodology used in the field program for gathering this information in the Morkill River valley could be applied to other terrain stability studies. By dividing areas into terrain units with similar characteristics, observations of slope angles within these units can be represented in histograms of frequency vs. slope angle to provide an easy to manage graphical depiction of a large amount of data which can be utilized to make judgments and to highlight potential concerns during the planning of future activities.

Knowledge of the limitations associated with the geology, geotechnical soil properties and landslide mechanisms is essential in these types of applications. As discussed in Chapter 7, acceptable slopes with angles up to 60° were noted in the silty soils; unweathered silty soils have high cohesion and may support steep slopes.

The knowledge of the threshold slope angles and soil properties can be applied to road construction techniques. Cuts should be avoided in slopes that exceed the threshold slope angles of 30° in the silty and sandy soils and 25° in the clayey soils. If cuts are to be made, suitable slope protection and stabilization in the form of retaining structures, vegetative material and/or geosynthetics will be required if sediment generation is of concern. Design of reinforcement or slope protection must be addressed on a site by site basis. Soil conditions, economics and acceptable risk will govern any design.

9.2 Suggestions for Further Research

This study of the engineering geology and geotechnical properties of the weakly cemented lake sediments in the Morkill River valley has produced several questions regarding the occurrence and properties of these soils. Questions as to the regional variations and depositional environments as well as more specific questions regarding the effects of not only calcite cementation but cementation in general need to be addressed.

The study in the Morkill River valley looked at the variation in types of sediments as well as the carbonate contents of the soils. Based on the assumed depositional environment and proximity to soluble bedrock, it could be assumed that sediments with similar properties are associated with soluble bedrock throughout western Canada. Therefore, regional studies as to the distribution of carbonate sediments in relation to soluble bedrock would be beneficial.

More specific studies are needed with respect to the effect of carbonate content on the geotechnical properties of soils. Of most importance is the distinction of the relative effects of calcite cement and calcite grains or clasts on the geotechnical properties of cemented soils. Common carbonate determination techniques address only total carbonate content but do not differentiate between the two forms. Visual inspection utilizing scanning electron microscopy is a method which can be used for a relative quantification but this is neither accessible or practical.

Also of interest is the variation of carbonate content with particle size. In this study and others, the higher apparent carbonate contents and densities in soils comprised mainly of silt size particles has been noted. It appears that a correlation, most likely between specific surface area and carbonate content, could be established to describe this occurrence.

This study addressed the removal of the cement in the soils of the Morkill River valley and the effect on the loss of shear strength and slope stability. Knowing that this process takes place in surficial soils, there is the possibility of this mechanism leading to instability in deeper deposits. Studies on the glaciomarine soils of Eastern Canada and Scandinavia have shown that leaching is a mechanism that contributes to instability in landslides tens of metres in depth. The effects of groundwater flow in higher permeability varves in the subsurface may be similar to the effects in glaciolacustrine sediments in Western Canada.

A topic not discussed in this thesis is the rate of retrogression of the rupture surfaces of specific landslides in the weakly cemented sediments. Observations at slide 66044:01 showed evidence of multiple flow events in the accumulated debris, indicating that the landslide has been retrogressing over many years A historical airphoto review of large landslides in the weakly cemented sediments may provide more insight into the rate at which these landslides grow and then stabilize. This would provide information on the historical rates at which sediment had entered the drainage system.

Considering the above, it is clear that there needs to be a greater dialogue and more interdisciplinary studies of the formation of cementation bonds. Researchers from the fields of geotechnical engineering, geomorphology and soil science would be able to provide a more complete background needed to get a better understanding with respect to these problems.

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Appendix A: Landslide Inventory Tables

The following 30 landslide inventory tables provide information that I obtained during a reconnaissance airphoto review of the Morkill River valley. A description of the terminology used and the airphotos interpreted is provided in Section 3.5 of the thesis document. This inventory covers the Morkill River valley and describes 81 landslides. Airphoto overlays corresponding to these tables and identified by airphoto number are presented in the same in Appendix B. The order of presentation begins at the mouth of the Morkill River and progresses to the east, along the river, to Renshaw Creek, as shown in Figure 5.1.

MORKILL WATERSHED LANDSLIDE INVENTORY

Air Photo: BCB91081 No. 008

REFERENCE	81008:01	81008:02
Location		
X-Coord.	-3	-5
Y-Coord.	8	10
UTM Easting	651750	652450
UTM Northing	5944750	5944550
Elevation	780	780
UNIT DESCRIPTION (Office)		
Genetic Origin	L	L
Surface Expression		
Thickness	b	b
Slope Angle	m	m
Aspect	SW	SW
Drainage	M	M
UNIT DESCRIPTION (Field)		
Soil Type: Major		
Soil Type: Minor		
Effervescence		
Natural Slope Angle (Degrees)		
Slope Curvature		
Aspect (Degrees)		
Drainage Class		
LANDSLIDE DESCRIPTION		
State of Activity	Dormant	Dormant
Distibution of Activity	-	-
Style of Activity	Single	Single
Material	Earth	Earth
Type	Flow	Flow
SURFACE OF RUPTURE		
Slope Angle (Degrees)		
Length (metres)	340	520
Width (metres)	160	350
Depth (metres)		
DISPLACED MASS		
Slope Angle (Degrees)		
Length (metres)	300	320
Width (metres)	160	340
Depth (metres)		
CAUSES	1c, 2g	1c, 2g

MORKILL WATERSHED LANDSLIDE INVENTORY

Air Photo: BCB91081 No. 119

REFERENCE	81119:01	81119:02	81119:03	81119:04
Location				
X-Coord.	6	9	5.5	7.5
Y-Coord.	4	2	0	-2.5
UTM Northing	5946350	5946080	5943800	5945450
UTM Easting	659630	659850	660330	659700
Elevation (m.a.s.l)	1380	1440	1430	1520
UNIT DESCRIPTION (Office)				
Genetic Origin	C	C or L	C or L	C or L
Surface Expression				
Thickness	v	v	v	v
Slope Angle	a	a	a	a
Aspect	SW	SW	NE	NE
Drainage	M	M	M	M
UNIT DESCRIPTION (Field)				
Soil Type: Major				
Soil Type: Minor				
Effervescence				
Natural Slope Angle (Degrees)				
Slope Curvature				
Aspect (Degrees)				
Drainage Class				
LANDSLIDE DESCRIPTION				
State of Activity	Relict	Dormant	Dormant	Dormant
Distibution of Activity	-	-	-	-
Style of Activity	Single	Single	Single	Single
Material	Rock	Earth	Earth	Earth
Type	Slide	Flow	Flow	Flow
SURFACE OF RUPTURE				
Slope Angle (Degrees)				
Length (metres)	730	620	460	500
Width (metres)	540	150	200	160
Depth (metres)				
DISPLACED MASS				
Slope Angle (Degrees)				
Length (metres)	600	320	300	-
Width (metres)	600	150	120	-
Depth (metres)				
CAUSES	1g	1c, 2c	1c, 2c	1c, 2c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo: BCB91081 No. 092

REFERENCE	81092:01	81092:02
Location		
X-Coord.	0	2
Y-Coord.	7	6.5
UTM Easting	689750	690150
UTM Northing	5948000	5948000
Elevation (m.a.s.l)	1340	1330
UNIT DESCRIPTION (Office)		
Genetic Origin	L	L
Surface Expression		
Thickness	v	v
Slope Angle	a	a
Aspect	S	S
Drainage	M	M
UNIT DESCRIPTION (Field)		
Soil Type: Major		
Soil Type: Minor		
Effervescence		
Natural Slope Angle (Degrees)		
Slope Curvature		
Aspect (Degrees)		
Drainage Class		
LANDSLIDE DESCRIPTION		
State of Activity	Relict	Relict
Distibution of Activity	-	-
Style of Activity	Composite	Composite
Material	Earth	Earth
Type	Flow	Flow
SURFACE OF RUPTURE		
Slope Angle (Degrees)		
Length (metres)	780	800
Width (metres)	340	500
Depth (metres)		
DISPLACED MASS		
Slope Angle (Degrees)		
Length (metres)	800	800
Width (metres)	200	300
Depth (metres)		
CAUSES	1c, 2g	1c, 2g

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91081 No. 090

REFERENCE	81090:01	81090:02	81090:03	81090:04
Location				
X-Coord.	-9.5	9	-8	6
Y-Coord.	5.5	5.5	5	6
UTM Easting	6890350	690450	690600	690950
UTM Northing	5947750	5947750	5947700	5947850
Elevation	1120	1120	1100	1220
UNIT DESCRIPTION				
Genetic Origin	L	L	L	L
Surface Expression				
Thickness	b	b	b	b
Slope Angle	a	j	k	k
Aspect	S	W	E	S
Drainage	M	M	M	M
UNIT DESCRIPTION (Field)				
Soil Type: Major				
Soil Type: Minor				
Effervescence				
Natural Slope Angle (Degrees)				
Slope Curvature				
Aspect (Degrees)				
Drainage Class				
LANDSLIDE DESCRIPTION				
State of Activity	Dormant	Active	Active	Dormant
Distibution of Activity	-	Advancing	Widening	-
Style of Activity	Composite	Single	Single	Single
Material	Earth	Earth	Earth	Earth
Type	Flow	Slide	Slide	Slide
SURFACE OF RUPTURE				
Slope Angle (Degrees)				
Length (metres)	330	110	240	460
Width (metres)	110	100	100	430
Depth (metres)				
DISPLACED MASS				
Slope Angle (Degrees)				
Length (metres)	-	-	190	-
Width (metres)	-	-	170	-
Depth (metres)				
CAUSES	2c, 1c	1c	2c, 1c	2c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91081 No. 090

REFERENCE	81090:05	81090:06	81090:07	81090:08
Location				
X-Coord.	-4.5	-6	-2	0.5
Y-Coord.	4.5	3	4.5	5
UTM Easting	691350	691050	691700	692200
UTM Northing	5947600	5947200	5947620	5947700
Elevation (m.a.s.l)	1100	1040	1050	1120
UNIT DESCRIPTION				
Genetic Origin	L	L	L	L
Surface Expression				
Thickness	b	b	b	b
Slope Angle	k	a	a	a
Aspect	SW	NE	SE	S
Drainage	M	M	M	M
UNIT DESCRIPTION (Field)				
Soil Type: Major				
Soil Type: Minor				
Effervescence				
Natural Slope Angle (Degrees)				
Slope Curvature				
Aspect (Degrees)				
Drainage Class				
LANDSLIDE DESCRIPTION				
State of Activity	Active	Active	Active	Active
Distibution of Activity	Advancing	Widening	Enlarging	Retrogressive
Style of Activity	Single	Single	Single	Composite
Material	Earth	Earth	Earth	Earth
Type	Slide	Slide	Slide	Flow
SURFACE OF RUPTURE				
Slope Angle (Degrees)				
Length (metres)	130	50	70	90
Width (metres)	140	200	90	15
Depth (metres)				
DISPLACED MASS				
Slope Angle (Degrees)				
Length (metres)	110	-	-	20
Width (metres)	140	-	-	20
Depth (metres)				
CAUSES	2c	2c	2c	2c, 1c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91091 No. 090

REFERENCE	81090:09	81090:10	81090:11	81090:12
Location				
X-Coord.	-3.5	-6	-7	6
Y-Coord.	-5.5	-7.5	-3	-6.5
UTM Easting	691700	691550	690450	693250
UTM Northing	5945675	5945500	5946100	5945950
Elevation (m.a.s.l)	1700	1800	1800	1900
UNIT DESCRIPTION				
Genetic Origin	R	R	R	R
Surface Expression	u	u	r	u
Thickness	-	-	-	-
Slope Angle	k	k		s
Aspect	NE	NE		W
Drainage	-	-		-
UNIT DESCRIPTION (Field)				
Soil Type: Major				
Soil Type: Minor				
Effervescence				
Natural Slope Angle (Degrees)				
Slope Curvature				
Aspect (Degrees)				
Drainage Class				
LANDSLIDE DESCRIPTION				
State of Activity	Active	Active	Relict	Active
Distibution of Activity	Diminishing	Diminishing	-	Diminishing
Style of Activity	Single	?	Complex	Composite
Material	Rock	Rock	Rock	Rock
Type	Fall	Fall	Topple	Fall
SURFACE OF RUPTURE				
Slope Angle (Degrees)				
Length (metres)	60	120	1300	330
Width (metres)	290	70	200	200
Depth (metres)				
DISPLACED MASS				
Slope Angle (Degrees)				
Length (metres)	200	-	-	300
Width (metres)	180	-	-	90
Depth (metres)				
CAUSES	1d, 1c	1c, 1d	1g, 2a	1c, 1e

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91081 No. 090

REFERENCE	81090:13	81090:14	81090:15	81090:16
Location				
X-Coord.	0.5	3	-4.5	0
Y-Coord.	6.5	2	7	-2
UTM Easting	692100	692650	691100	692150
UTM Northing	5948050	5947150	5948100	5946450
Elevation	1220	1340	1340	1260
UNIT DESCRIPTION				
Genetic Origin	L	L	L	L
Surface Expression				
Thickness	b	b	b	b
Slope Angle	k	a	a	a
Aspect	S	N	S	NW
Drainage	M	M	M	M
UNIT DESCRIPTION (Field)				
Soil Type: Major				
Soil Type: Minor				
Effervescence				
Natural Slope Angle (Degrees)				
Slope Curvature				
Aspect (Degrees)				
Drainage Class				
LANDSLIDE DESCRIPTION				
State of Activity	Dormant	Relict	Relict	Dormant
Distibution of Activity	-	-	-	-
Style of Activity	Composite	Composite	Composite	Single
Material	Earth	Earth	Earth	Earth
Type	Flow	Flow	Flow	Slide
SURFACE OF RUPTURE				
Slope Angle (Degrees)				
Length (metres)	420	660	600	70
Width (metres)	90	520	630	20
Depth (metres)				
DISPLACED MASS				
Slope Angle (Degrees)				
Length (metres)	140	-	520	-
Width (metres)	90	-	400	-
Depth (metres)				
CAUSES	1c	2c, 1c	1c, 2c	2c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91081 No. 090

REFERENCE	81090:17	81090:18
Location		
X-Coord.	-0.5	0.5
Y-Coord.	-3	-5
UTM Easting	692100	692250
UTM Northing	5946220	5945900
Elevation (m.a.s.l.)	1280	1310
UNIT DESCRIPTION		
Genetic Origin	L	L
Surface Expression		
Thickness	b	b
Slope Angle	a	a
Aspect	W	W
Drainage	M	M
UNIT DESCRIPTION (Field)		
Soil Type: Major		
Soil Type: Minor		
Effervescence		
Natural Slope Angle (Degrees)		
Slope Curvature		
Aspect (Degrees)		
Drainage Class		
LANDSLIDE DESCRIPTION		
State of Activity	Dormant	Dormant
Distibution of Activity	-	-
Style of Activity	Single	Single
Material	Earth	Earth
Type	Slide	Slide
SURFACE OF RUPTURE		
Slope Angle (Degrees)		
Length (metres)	50	140
Width (metres)	40	20
Depth (metres)		
DISPLACED MASS		
Slope Angle (Degrees)		
Length (metres)	-	-
Width (metres)	-	-
Depth (metres)		
CAUSES	2c	2c

MORKILL WATERSHED LANDSLIDE INVENTORY

Air Photo: BCB91066 No. 044

REFERENCE	66044:01	66044:02	66044:03
Location	Morkill 13 km (Forest)	Morkill 13 km (Forest)	CP550-1
X-Coord.	1.5	0.4	-4.5
Y-Coord.	-3	-4	-7
UTM Easting	658794	658558	657644
UTM Northing	5947663	5947364	5946931
Elevation (m.a.s.l)	860	840	740
UNIT DESCRIPTION			
Genetic Origin	L	L	
Surface Expression			
Thickness	b	b	
Slope Angle	a	a	
Aspect	NW	N	
Drainage	P	P	
UNIT DESCRIPTION (Field)			
Soil Type: Major	ML	ML	SP
Soil Type: Minor	SM/SP	SP/SM	SM/ML
Effervescence	Moderate	High	Moderate
Natural Slope Angle (Degrees)	45	45	45
Slope Curvature	Concave	Concave	Concave
Aspect (Degrees)	300	340	236
Drainage Class	Moderate	Moderate	Moderate
LANDSLIDE DESCRIPTION			
State of Activity	Active	Active	Active
Distibution of Activity	Retrogressive	Retrogressive	Diminishing
Style of Activity	Composite	Composite	Composite
Material	Earth	Earth	Earth
Type	Slide-Flow	Slide-Flow	Slide-Flow
SURFACE OF RUPTURE			
Slope Angle (Degrees)	43-51	45	40
Length (metres)	250	100	45
Width (metres)	250	80	15
Depth (metres)	Deep	Deep	2.5
DISPLACED MASS			
Slope Angle (Degrees)	Flat	35	21
Length (metres)	>500	>500	23
Width (metres)	~200	~200	27
Depth (metres)	>1.2	>1.2	1.2
CAUSES	1c	1c	1c,4d

MORKILL WATERSHED LANDSLIDE INVENTORY

Air Photo: BCB91066 No. 044

REFERENCE	66044:04	66044:06
Location	Morkill 13 km (Forest)	Morkill 13 km (Forest)
X-Coord.	-0.5	5-Feb
Y-Coord.	-3.5	-2
UTM Easting	658451	658839
UTM Northing	5947603	5947800
Elevation (m.a.s.l)	780	800
UNIT DESCRIPTION		
Genetic Origin		
Surface Expression		
Thickness		
Slope Angle		
Aspect		
Drainage		
UNIT DESCRIPTION (Field)		
Soil Type: Major	SM	SM
Soil Type: Minor	SP/SW	SP
Effervescence	Moderate	Mod-High
Natural Slope Angle (Degrees)	35	35
Slope Curvature	Concave	Concave
Aspect (Degrees)	65	310
Drainage Class	Moderate	Moderate
LANDSLIDE DESCRIPTION		
State of Activity	Active	Dormant
Distibution of Activity	Diminishing	-
Style of Activity	Multiple	Composite
Material	Earth	Earth
Type	Slide	Slide-Flow
SURFACE OF RUPTURE		
Slope Angle (Degrees)	44	59
Length (metres)	52	21
Width (metres)	28	60
Depth (metres)	3.6	8
DISPLACED MASS		
Slope Angle (Degrees)	Not seen	Not seen
Length (metres)		
Width (metres)		
Depth (metres)		
CAUSES	1c	1c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo: BCB91065 No. 235

REFERENCE	65235:01	65235:02	65235:04
Location		Morkill 25 5 km (River)	
X-Coord.	-7	-6.5	0
Y-Coord.	2.5	3.5	0
UTM Easting	666000	665910	667400
UTM Northing	5954000	5951484	5953550
Elevation (m.a.s.l)		780	
UNIT DESCRIPTION			
Genetic Origin	L	L	L
Surface Expression			
Thickness	b	b	b
Slope Angle	k	k	a
Aspect	NE	N	NW
Drainage	M	W	M
UNIT DESCRIPTION (Field)			
Soil Type: Major		SW	
Soil Type: Minor		ML/SP	
Effervescence		Mild	
Natural Slope Angle (Degrees)		44	
Slope Curvature		Concave	
Aspect (Degrees)		320	
Drainage Class		Well	
LANDSLIDE DESCRIPTION			
State of Activity	Dormant	Abandoned	Relict
Distibution of Activity	-	-	-
Style of Activity	Single	Multiple	Single
Material	Earth	Earth	Earth
Type	Slide	Slide	Flow
SURFACE OF RUPTURE			
Slope Angle (Degrees)		46	
Length (metres)	100	92	430
Width (metres)	270	73	160
Depth (metres)		1.5 to 4.5	
DISPLACED MASS			
Slope Angle (Degrees)		Flat (River)	170
Length (metres)	-	15	160
Width (metres)	-	93	
Depth (metres)		~2.0	
CAUSES	1c	2c,1c	1c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo: BCB91065 No. 235

REFERENCE	65235:05	65235:06	65235:07
Location		North of CP 302	North of CP 302
X-Coord.	0	-1.5	1
Y-Coord.	1	8	8
UTM Easting	667500	666810	669013
UTM Northing	5953800	5952438	5952600
Elevation (m.a.s.l)		900	820
UNIT DESCRIPTION			
Genetic Origin	L	L	L
Surface Expression			
Thickness	b	b	b
Slope Angle	a	a	a
Aspect	NW	E	S
Drainage	M	M	M
UNIT DESCRIPTION (Field)			
Soil Type: Major		ML	ML
Soil Type: Minor		SM/SP	
Effervescence		Moderate	Moderate
Natural Slope Angle (Degrees)		45	45
Slope Curvature		Concave	Convex
Aspect (Degrees)		45	220
Drainage Class		Moderate	Moderate
LANDSLIDE DESCRIPTION			
State of Activity	Relict	Active	Active
Distibution of Activity	-	Retrogressive	Diminshing
Style of Activity	Single	Composite	Multiple
Material	Earth	Earth	Earth
Type	Flow	Slide-Flow	Slide
SURFACE OF RUPTURE			
Slope Angle (Degrees)		48	50
Length (metres)	290	135	10
Width (metres)	200	55	13
Depth (metres)		7	2
DISPLACED MASS			
Slope Angle (Degrees)	210	29	35
Length (metres)	180	64+	25
Width (metres)		45	10
Depth (metres)		>5	1
CAUSES	1c	1c	1c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo: BCB91065 No. 235

REFERENCE	65235:09	65235:11	65235:12
Location	CP302 (River)	CP302-1	Morkill 28.5km (River)
X-Coord.	-4	-3	9
Y-Coord.	3.5	2	5
UTM Easting	666740	666535	668925
UTM Northing	5951699	5951898	5952107
Elevation (m.a.s.l)	750	780	760
UNIT DESCRIPTION			
Genetic Origin			
Surface Expression			
Thickness			
Slope Angle			
Aspect			
Drainage			
UNIT DESCRIPTION (Field)			
Soil Type: Major	SW	ML	SP
Soil Type: Minor	SM/SP		SM
Effervescence	Mild	Mild	Moderate
Natural Slope Angle (Degrees)	35	35	44
Slope Curvature	Concave	Concave	Concave
Aspect (Degrees)	120	90	210
Drainage Class	Well	Irregular	Well
LANDSLIDE DESCRIPTION			
State of Activity	Active	Dormant	Abandoned
Distibution of Activity	etrogressiv	-	-
Style of Activity	Multiple	Composite	Composite
Material	Earth	Earth	Earth
Type	Slide	Slide-Flow	Slide-Flow
SURFACE OF RUPTURE			
Slope Angle (Degrees)	34	35	40
Length (metres)	34	36	18
Width (metres)	23	12	12
Depth (metres)	1.5	1	1.7
DISPLACED MASS			
Slope Angle (Degrees)	Into River	Flat (Marsh)	33
Length (metres)	-	-	41
Width (metres)	-	-	12
Depth (metres)	-		
CAUSES	2c,1c	4d,1c	2c,1c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo: BCB91065 No. 233

REFERENCE	65233:01	65233:02	65233:03	65233:04
Location				
X-Coord.	-5	-6	2.5	-0.5
Y-Coord.	5	3	-2	4
UTM Easting	662960	662780	663380	663770
UTM Northing	5951575	5951270	5951100	5951450
Elevation (m.a.s.l)	900	800	800	840
UNIT DESCRIPTION				
Genetic Origin	L	L	L	L
Surface Expression				
Thickness	b	b	b	b
Slope Angle	k	a	k	s
Aspect	NW	SW	SE	S
Drainage	M	M	W	M
UNIT DESCRIPTION (Field)				
Soil Type: Major				
Soil Type: Minor				
Effervescence				
Natural Slope Angle (Degrees)				
Slope Curvature				
Aspect (Degrees)				
Drainage Class				
LANDSLIDE DESCRIPTION				
State of Activity	Active	Active	Active	Abandoned
Distibution of Activity	Advancing	Diminishing	Retrogressive	-
Style of Activity	Single	Single	Single	Single
Material	Earth	Earth	Earth	Earth
Type	Slide	Slide	Slide	Slide
SURFACE OF RUPTURE				
Slope Angle (Degrees)				
Length (metres)	100	300	260	240
Width (metres)	400	100	260	140
Depth (metres)				
DISPLACED MASS				
Slope Angle (Degrees)				
Length (metres)	-	340	-	250
Width (metres)	-	100	-	140
Depth (metres)				
CAUSES	1c, 2c	2c, 1c	2c	2c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91065 No. 229

REFERENCE	65229:01	65229:02
Location		
X-Coord.	11	8.5
Y-Coord.	2.5	3.5
UTM Easting	659100	658800
UTM Northing	5951100	5951250
Elevation (m.a.s.l)	780	780
UNIT DESCRIPTION		
Genetic Origin	L	L
Surface Expression		
Thickness	b	b
Slope Angle	k	k
Aspect	SE	S
Drainage	M	W
UNIT DESCRIPTION (Field)		
Soil Type: Major		
Soil Type: Minor		
Effervescence		
Natural Slope Angle (Degrees)		
Slope Curvature		
Aspect (Degrees)		
Drainage Class		
LANDSLIDE DESCRIPTION		
State of Activity	Active	Active
Distibution of Activity	Dimishing	Abandoned
Style of Activity	Single	Single
Material	Earth	Earth
Type	Slide	Slide
SURFACE OF RUPTURE		
Slope Angle (Degrees)		
Length (metres)	50	150
Width (metres)	40	110
Depth (metres)		
DISPLACED MASS		
Slope Angle (Degrees)		
Length (metres)	-	140
Width (metres)	-	80
Depth (metres)		
CAUSES	2c	2g, 2c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91065 No. 237

REFERENCE	65237:02	65237:03	65237:04	65237:05
Location	CP340 Rd (2km)	CP340 Rd (1.5km)	CP340 Rd (1.8 km)	CP340 Rd (2.1 km)
X-Coord.	-3	-2	-2.5	-3
Y-Coord.	8	7.5	8	7.5
UTM Easting	669690	669901	669710	669682
UTM Northing	5952537	5952352	5952350	5952484
Elevation (m.a.s.l)	860	880	860	860
UNIT DESCRIPTION				
Genetic Origin				
Surface Expression				
Thickness				
Slope Angle				
Aspect				
Drainage				
UNIT DESCRIPTION (Field)				
Soil Type: Major	SW	SM	SW	SP
Soil Type: Minor	SM	SP	ML/SM	
Effervescence	Moderate	Moderate	Moderate	Moderate
Natural Slope Angle (Degrees)	35	31	40	35
Slope Curvature	Straight	Concave	Concave	Concave
Aspect (Degrees)	260	80	50	270
Drainage Class	Moderate	Moderate	Moderate	Moderate
LANDSLIDE DESCRIPTION				
State of Activity	Active	Active	Suspended	Active
Distibution of Activity	Diminishing	Retrogressive	-	Diminishing
Style of Activity	Multiple	Composite	Single	Multiple
Material	Earth	Earth	Earth	Earth
Type	Slide	Slide-Flow	Slide	Slide
SURFACE OF RUPTURE				
Slope Angle (Degrees)	37	45	42	35
Length (metres)	52	59	22	39
Width (metres)	45	18	115	29
Depth (metres)	1	3.8	2	2.8
DISPLACED MASS				
Slope Angle (Degrees)	22	30	35	25
Length (metres)	65	100	50	36
Width (metres)	36	6	115	30
Depth (metres)	6	30	1.5	
CAUSES	4d,1c	1c	1c,4d	4d,1c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91065 No. 237

REFERENCE	65237:06	65237:07
Location	CP 340 Rd (2.2 km)	Morkill 29.5km (River)
X-Coord.	-3.5	9
Y-Coord.	7	-6
UTM Easting	669577	668994
UTM Northing	5952200	5952470
Elevation (m.a.s.l)	860	760
UNIT DESCRIPTION		
Genetic Origin		
Surface Expression		
Thickness		
Slope Angle		
Aspect		
Drainage		
UNIT DESCRIPTION (Field)		
Soil Type: Major	SP	GW
Soil Type: Minor	SM	SM/ML
Effervescence	Mild	Moderate
Natural Slope Angle (Degrees)	37	40
Slope Curvature	Concave	Concave
Aspect (Degrees)	280	100
Drainage Class	Moderate	Well
LANDSLIDE DESCRIPTION		
State of Activity	Active	Active
Distibution of Activity	Diminishing	Diminishing
Style of Activity	Single	Multiple
Material	Earth	Earth
Type	Slide	Slide
SURFACE OF RUPTURE		
Slope Angle (Degrees)	45	45
Length (metres)	70	17
Width (metres)	23	16
Depth (metres)	1.2	2.5
DISPLACED MASS		
Slope Angle (Degrees)	35	25
Length (metres)	60	33
Width (metres)	23	10
Depth (metres)	Forest	1
CAUSES	1c,4d	2c,1c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB91065 No. 239

REFERENCE	65239:01	65239:02	65239:03	65239:04
Location	Morkill 36 km (River)	Morkill 35 km (River)		
X-Coord.	-6	-4.5	6	7
Y-Coord.	-2	-3	-8.5	-4
UTM Easting	672766	673180	675250	675475
UTM Northing	5951075	5950869	5949900	5950600
Elevation (m.a.s.l)	950	940		
UNIT DESCRIPTION				
Genetic Origin	L	L	C	L
Surface Expression				
Thickness	b	b	v	b
Slope Angle	k	k	k	k
Aspect	S	S	NW	SE
Drainage	W	W	M	W
UNIT DESCRIPTION (Field)				
Soil Type: Major	ML	ML		
Soil Type: Minor	SP/SM	SP/SM		
Effervescence	High	Moderate		
Natural Slope Angle (Degrees)	50	45		
Slope Curvature	Straight	Straight		
Aspect (Degrees)	180	200		
Drainage Class	Well	Moderate		
LANDSLIDE DESCRIPTION				
State of Activity	Active	Stabilized	Dormant	Active
Distibution of Activity	Retrogressive	-	-	Retrogressive
Style of Activity	Composite	Multiple	Single	Single
Material	Earth	Earth	Earth	Earth
Type	Slide-Flow	Slide	Slide	Slide
SURFACE OF RUPTURE				
Slope Angle (Degrees)	50	50		
Length (metres)	160		300	120
Width (metres)	100		180	130
Depth (metres)	-			
DISPLACED MASS				
Slope Angle (Degrees)	River	Not seen		
Length (metres)			320	-
Width (metres)			180	-
Depth (metres)				
CAUSES	2c,1c	2c,1c	2f	2c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo: BCB91065 No. 241

REFERENCE	65241:01	65241:02	65241:03	65241:04
Location				
X-Coord.	-5.5	4	7	7
Y-Coord.	-3	-6	-7.5	-9
UTM Easting	676200	677700	678380	678150
UTM Northing	5950350	5949750	5949900	5949650
Elevation (m.a.s.l)	1050	1520	1460	1500
UNIT DESCRIPTION				
Genetic Origin	L	R	R	R
Surface Expression		h		
Thickness	b	-		
Slope Angle	a	k	k	k
Aspect	NE	N	N	N
Drainage	M	-	-	-
UNIT DESCRIPTION (Field)				
Soil Type: Major				
Soil Type: Minor				
Effervescence				
Natural Slope Angle (Degrees)				
Slope Curvature				
Aspect (Degrees)				
Drainage Class				
LANDSLIDE DESCRIPTION				
State of Activity	Dormant	Active	Active	Active
Distibution of Activity	-	-	-	-
Style of Activity	Single	Complex	Complex	Complex
Material	Earth	Rock	Rock	Rock
Type	Flow	Fall	Fall	Fall
SURFACE OF RUPTURE				
Slope Angle (Degrees)				
Length (metres)	400	100	40	40
Width (metres)	300	500	50	90
Depth (metres)				
DISPLACED MASS				
Slope Angle (Degrees)				
Length (metres)	300	240	40	30
Width (metres)	360	480	80	160
Depth (metres)				
CAUSES	2c	1g, 1d	1g, 1d	1g, 1d

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo: BCB91065 No. 241

REFERENCE	65241:05	65241:06
Location		
X-Coord.	8	-7
Y-Coord.	3	-6
UTM Easting	678300	676100
UTM Northing	5952100	5949550
Elevation (m.a.s.l)	1040	1540
UNIT DESCRIPTION		
Genetic Origin	L	R
Surface Expression		
Thickness	b	
Slope Angle	a	a
Aspect	S	NE
Drainage	M	M
UNIT DESCRIPTION (Field)		
Soil Type: Major		
Soil Type: Minor		
Effervescence		
Natural Slope Angle (Degrees)		
Slope Curvature		
Aspect (Degrees)		
Drainage Class		
LANDSLIDE DESCRIPTION		
State of Activity	Dormant	Relict
Distibution of Activity	-	
Style of Activity	Single	Complex
Material	Earth	Rock
Type	Slide	Slide
SURFACE OF RUPTURE		
Slope Angle (Degrees)		
Length (metres)	520	240
Width (metres)	320	180
Depth (metres)		
DISPLACED MASS		
Slope Angle (Degrees)		
Length (metres)	500	200
Width (metres)	280	160
Depth (metres)		
CAUSES	2c	2a

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91065 No. 243

REFERENCE	65243:01	65243:02	65243:03	65243:04
Location			Morkill 46.5 km	Morkill 46.5 km
X-Coord.	-8.5	5	8	6
Y-Coord.	1	-0.5	-2	-3
UTM Easting	678800	679200	681232	681259
UTM Northing	5951300	5951200	5951242	5951229
Elevation (m.a.s.l)	900	1000	970	970
UNIT DESCRIPTION				
Genetic Origin	L	L	L	L
Surface Expression				
Thickness	b	b	b	b
Slope Angle	a	k	a	a
Aspect	N	W	SW	SW
Drainage	M	M	M	M
UNIT DESCRIPTION (Field)				
Soil Type: Major			SP	SP
Soil Type: Minor				
Effervescence			Moderate	Moderate
Natural Slope Angle (Degrees)			35	35
Slope Curvature			Concave	Concave
Aspect (Degrees)			320	320
Drainage Class			Moderate	Moderate
LANDSLIDE DESCRIPTION				
State of Activity	Dormant	Relict	Active	Active
Distibution of Activity	-	-		
Style of Activity	Single	Single	Single	Single
Material	Earth	Earth	Earth	Earth
Type	Slide	Slide	Slide	Slide
SURFACE OF RUPTURE				
Slope Angle (Degrees)			46	65-74
Length (metres)	240	150	20	28
Width (metres)	180	260	23	15
Depth (metres)			2	1.5
DISPLACED MASS				
Slope Angle (Degrees)			18	16
Length (metres)	200	-	16	15
Width (metres)	160	-	23	20
Depth (metres)			1.5	1.5
CAUSES	2c	2c, 1a	1c,4a	1c,4a

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo: BCB91065 No. 245

REFERENCE	65245:01
Location	
X-Coord.	0
Y-Coord.	-7
UTM Easting	683500
UTM Northing	5950300
Elevation (m.a.s.l)	1100
UNIT DESCRIPTION	
Genetic Origin	R
Surface Expression	u
Thickness	-
Slope Angle	a
Aspect	SW
Drainage	W
UNIT DESCRIPTION (Field)	
Soil Type: Major	
Soil Type: Minor	
Effervescence	
Natural Slope Angle (Degrees)	
Slope Curvature	
Aspect (Degrees)	
Drainage Class	
LANDSLIDE DESCRIPTION	
State of Activity	Relict
Distibution of Activity	-
Style of Activity	Complex
Material	Rock
Type	Slide
SURFACE OF RUPTURE	
Slope Angle (Degrees)	
Length (metres)	1150
Width (metres)	740
Depth (metres)	
DISPLACED MASS	
Slope Angle (Degrees)	
Length (metres)	400
Width (metres)	1000
Depth (metres)	
CAUSES	2a, 1f

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo: BCB91066 No. 025

REFERENCE	66025:01	66025:02
Location		
X-Coord.	3	6.5
Y-Coord.	-6.5	7
UTM Easting	687450	688100
UTM Northing	5948050	5947850
Elevation (m.a.s.l)	1100	1040
UNIT DESCRIPTION		
Genetic Origin	L	L
Surface Expression		
Thickness	b	b
Slope Angle	k	k
Aspect	S	S
Drainage	M	M
UNIT DESCRIPTION (Field)		
Soil Type: Major		
Soil Type: Minor		
Effervescence		
Natural Slope Angle (Degrees)		
Slope Curvature		
Aspect (Degrees)		
Drainage Class		
LANDSLIDE DESCRIPTION		
State of Activity	Active	Active
Distibution of Activity	Widening	Widening
Style of Activity	Single	Single
Material	Earth	Earth
Type	Slide	Slide
SURFACE OF RUPTURE		
Slope Angle (Degrees)		
Length (metres)	130	60
Width (metres)	240	20
Depth (metres)		
DISPLACED MASS		
Slope Angle (Degrees)		
Length (metres)	-	-
Width (metres)	-	-
Depth (metres)		
CAUSES	2c	2c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo: BCB91066 No. 022

REFERENCE	66022:01	66022:02
Location		
X-Coord.	0	4
Y-Coord.	0	0
UTM Easting	691400	691900
UTM Northing	5959600	5950000
Elevation (m.a.s.l)	1860	1900
UNIT DESCRIPTION		
Genetic Origin	R	R
Surface Expression	u	u
Thickness	-	-
Slope Angle	k	k
Aspect	S	S
Drainage	-	-
UNIT DESCRIPTION (Field)		
Soil Type: Major		
Soil Type: Minor		
Effervescence		
Natural Slope Angle (Degrees)		
Slope Curvature		
Aspect (Degrees)		
Drainage Class		
LANDSLIDE DESCRIPTION		
State of Activity	Active	Relict
Distibution of Activity	Dimishing	-
Style of Activity	Complex	Complex
Material	Rock	Rock
Type	Slide	Slide
SURFACE OF RUPTURE		
Slope Angle (Degrees)		
Length (metres)	1200	1500
Width (metres)	800	1200
Depth (metres)		
DISPLACED MASS		
Slope Angle (Degrees)		
Length (metres)	1300	-
Width (metres)	900	-
Depth (metres)		
CAUSES	2a, 1f	2a, 1f

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91066 No. 020

REFERENCE	66020:01	66020:02	66020:03	66020:04
Location				
X-Coord.	-6.5	-4	-1	3
Y-Coord.	-2	-7	-8	-9
UTM Easting	693150	693350	693800	694550
UTM Norhing	5948850	5948150	5947875	5947675
Elevation (m.a.s.l)	1200	1160	1120	1160
UNIT DESCRIPTION				
Genetic Origin	C	L	L	L
Surface Expression				
Thickness	v	b	b	b
Slope Angle	s	k	a	k
Aspect	SW	SE	NE	N
Drainage	M	M	M	M
UNIT DESCRIPTION (Field)				
Soil Type: Major				
Soil Type: Minor				
Effervescence				
Natural Slope Angle (Degrees)				
Slope Curvature				
Aspect (Degrees)				
Drainage Class				
LANDSLIDE DESCRIPTION				
State of Activity	Active	Active	Active	Active
Distibution of Activity	Diminishing	Widening	Retrogressive	Widening
Style of Activity	Single	Single	Single	Single
Material	Earth	Earth	Earth	Earth
Type	Slide	Slide	Slide	Slide
SURFACE OF RUPTURE				
Slope Angle (Degrees)				
Length (metres)	100	180	180	180
Width (metres)	40	180	250	160
Depth (metres)				
DISPLACED MASS				
Slope Angle (Degrees)				
Length (metres)	-	-	160	-
Width (metres)	-	-	200	-
Depth (metres)				
CAUSES	1f	2c	2c	2c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91066 No. 020

REFERENCE	66020:05	66020:06	66020:07	66020:08
Location				
X-Coord.	4.5	6.5	6.5	10.5
Y-Coord.	-8.5	-4	-5	-6.5
UTM Easting	694850	695200	695200	695900
UTM Norhing	5947750	5948550	5948400	5948100
Elevation (m.a.s.l)	1180	1200	1130	1140
UNIT DESCRIPTION				
Genetic Origin	L	L	L	L
Surface Expression				
Thickness	b	b	b	b
Slope Angle	k	k	k	k
Aspect	N	S	S	N
Drainage	M	M	M	M
UNIT DESCRIPTION (Field)				
Soil Type: Major				
Soil Type: Minor				
Effervescence				
Natural Slope Angle (Degrees)				
Slope Curvature				
Aspect (Degrees)				
Drainage Class				
LANDSLIDE DESCRIPTION				
State of Activity	Active	Acitve	Active	Active
Distibution of Activity	Retrogressiv	Dimishing	Widening	Widening
Style of Activity	Single	Single	Single	Single
Material	Earth	Earth	Earth	Earth
Type	Slide	Flow	Slide	Slide
SURFACE OF RUPTURE				
Slope Angle (Degrees)				
Length (metres)	250	110	80	110
Width (metres)	150	20	200	110
Depth (metres)				
DISPLACED MASS				
Slope Angle (Degrees)				
Length (metres)	170	60	-	-
Width (metres)	150	50	-	-
Depth (metres)				
CAUSES	2c	1c	2c	2c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91066 No. 027

REFERENCE	66027:01	66027:02	66027:03	66027:04
Location				
X-Coord.	0.5	2.5	5.5	8.5
Y-Coord.	1	-1.5	0	-3.5
UTM Easting	684100	684500	685100	685600
UTM Northing	5949400	5948675	5949100	5948350
Elevation (m.a.s.l)				
UNIT DESCRIPTION (Office)				
Genetic Origin	L	L	L	L
Surface Expression				
Thickness	b	b	b	b
Slope Angle	k	a	k	a
Aspect	S	NE	S	NE
Drainage	M	M	M	M
UNIT DESCRIPTION (Field)				
Soil Type: Major				
Soil Type: Minor				
Effervescence				
Natural Slope Angle (Degrees)				
Slope Curvature				
Aspect (Degrees)				
Drainage Class				
LANDSLIDE DESCRIPTION				
State of Activity	Active	Suspended	Active	Active
Distibution of Activity	Widening	-	Widening	Retrogressive
Style of Activity	Single	Single	Composite	Single
Material	Earth	Earth	Earth	Earth
Type	Slide	Slide	Slide	Flow
SURFACE OF RUPTURE				
Slope Angle (Degrees)				
Length (metres)	200	160	240	140
Width (metres)	100	180	80	40
Depth (metres)				
DISPLACED MASS				
Slope Angle (Degrees)				
Length (metres)	-	-	-	120
Width (metres)	-	-	-	130
Depth (metres)				
CAUSES	2c	2c	2c, 1c	2c, 1c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91066 No. 027

REFERENCE	66027:05	66027:06
Location		
X-Coord.	0	4.5
Y-Coord.	3	2
UTM Easting	684250	684700
UTM Northing	5949650	5949500
Elevation (m.a.s.l)		
UNIT DESCRIPTION (Office)		
Genetic Origin	L	L
Surface Expression		
Thickness	b	b
Slope Angle	a	a
Aspect	SW	SE
Drainage	M	M
UNIT DESCRIPTION (Field)		
Soil Type: Major		
Soil Type: Minor		
Effervescence		
Natural Slope Angle (Degrees)		
Slope Curvature		
Aspect (Degrees)		
Drainage Class		
LANDSLIDE DESCRIPTION		
State of Activity	Relict	Suspended
Distibution of Activity		-
Style of Activity	Single	Single
Material	Earth	Earth
Type	Flow	Slide
SURFACE OF RUPTURE		
Slope Angle (Degrees)		
Length (metres)	300	200
Width (metres)	360	120
Depth (metres)		
DISPLACED MASS		
Slope Angle (Degrees)		
Length (metres)	300	150
Width (metres)	50	100
Depth (metres)		
CAUSES	1c	1c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91081 No. 086

REFERENCE	81086:01	81086:02	81086:03	81086:04
Location				
X-Coord.	-2	0	6.5	8
Y-Coord.	6.5	8	0	-2
UTM Easting	697350	697650		697750
UTM Northing	5947700	5947850		5946750
Elevation (m.a.s.l)				
UNIT DESCRIPTION (Office)				
Genetic Origin	L	C	L	L
Surface Expression				
Thickness	b	v	b	b
Slope Angle	a	k	a	j
Aspect	NE	S	W	NE
Drainage	M	M	M	P
UNIT DESCRIPTION (Field)				
Soil Type: Major				
Soil Type: Minor				
Effervescence				
Natural Slope Angle (Degrees)				
Slope Curvature				
Aspect (Degrees)				
Drainage Class				
LANDSLIDE DESCRIPTION				
State of Activity	Active	Active	Suspended	Relict
Distibution of Activity	Widening	Diminishing	-	-
Style of Activity	Single	Single	Single	Composite
Material	Earth	Earth	Earth	Earth
Type	Slide	Slide	Slie	Slide
SURFACE OF RUPTURE				
Slope Angle (Degrees)				
Length (metres)	140	70	90	460
Width (metres)	180	40	130	600
Depth (metres)				
DISPLACED MASS				
Slope Angle (Degrees)				
Length (metres)	-	50	-	500
Width (metres)	-	30	-	600
Depth (metres)				
CAUSES	2c	1f, 1c	1c, 2c	2c, 1c

MORKILL RIVER LANDSLIDE INVENTORY

Air Photo BCB 91081 No. 086

REFERENCE	81086:05	81086:06	81086:07
Location			
X-Coord.	9	8.5	9
Y-Coord.	-3.5	-5	-6
UTM Easting	698100	698650	698700
UTM Northing	5946725	5946400	5946150
Elevation (m.a.s.l)			
UNIT DESCRIPTION (Office)			
Genetic Origin	L	L	L
Surface Expression			
Thickness	b	b	b
Slope Angle	a	a	a
Aspect	E	E	E
Drainage	M	M	M
UNIT DESCRIPTION (Field)			
Soil Type: Major			
Soil Type: Minor			
Effervescence			
Natural Slope Angle (Degrees)			
Slope Curvature			
Aspect (Degrees)			
Drainage Class			
LANDSLIDE DESCRIPTION			
State of Activity	Active	Dormant	Dormant
Distibution of Activity	Widening	-	-
Style of Activity	Single	Composite	Composite
Material	Earth	Earth	Earth
Type	Slide	Flow	Flow
SURFACE OF RUPTURE			
Slope Angle (Degrees)			
Length (metres)	280	170	180
Width (metres)	480	130	150
Depth (metres)			
DISPLACED MASS			
Slope Angle (Degrees)			
Length (metres)	210	360	240
Width (metres)	250	30	40
Depth (metres)			
CAUSES	2c	1c, 2g	1c, 2g

Appendix B: Airphoto Overlays

This appendix includes airphoto overlays that I completed during the preliminary reconnaissance study based on 1:20000 scale airphotos from the following flight lines:

Photo I.D	Year	Scale
• 30BCB91065	1991	1:20,000
• 30BCB91066	1991	1:20,000
• 30BCB91081	1991	1:20,000
• 30BCB91089	1991	1:20,000

The landslides noted during the initial study were further supplemented with observations taken during the field investigation. Airphoto overlays are presented from the mouth of the Morkill River, to the east, to Renshaw Creek, to the east. The area covered is shown on Figure 5.1. This order corresponds with the order of the landslide inventory tables presented in Appendix A.

The following symbols are utilized on the airphoto overlays:

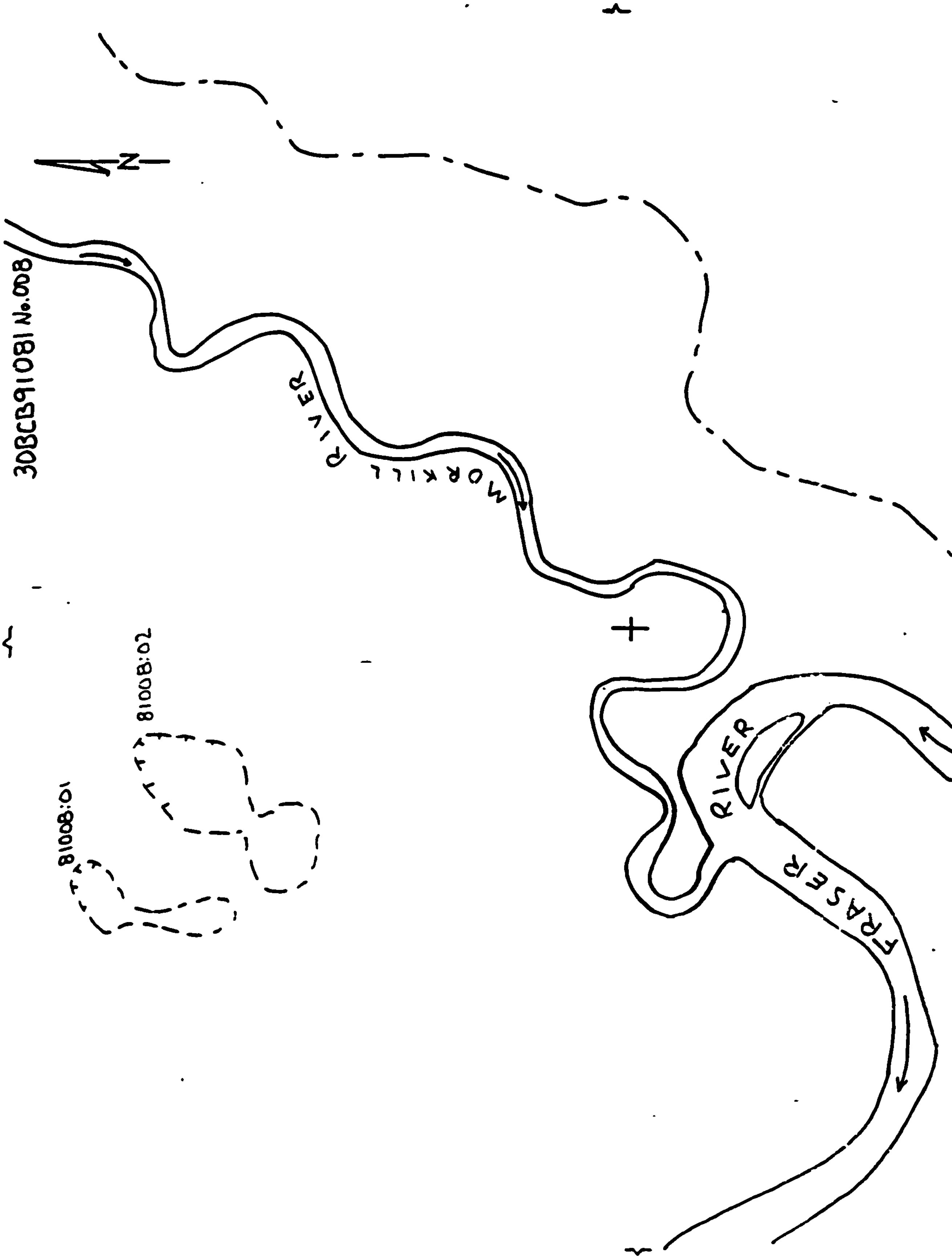
Landslide boundary-certain

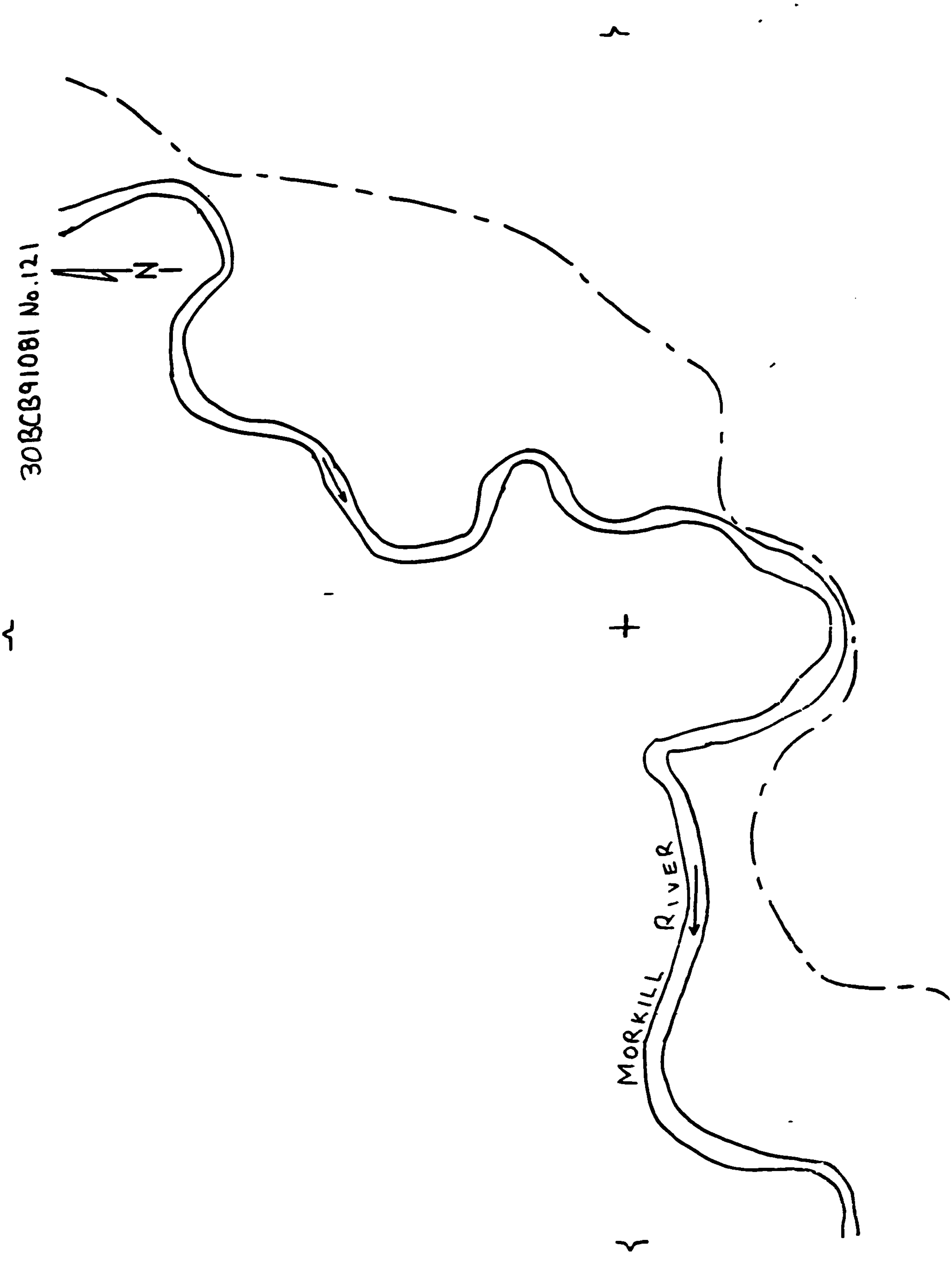
Landslide boundary-approximate

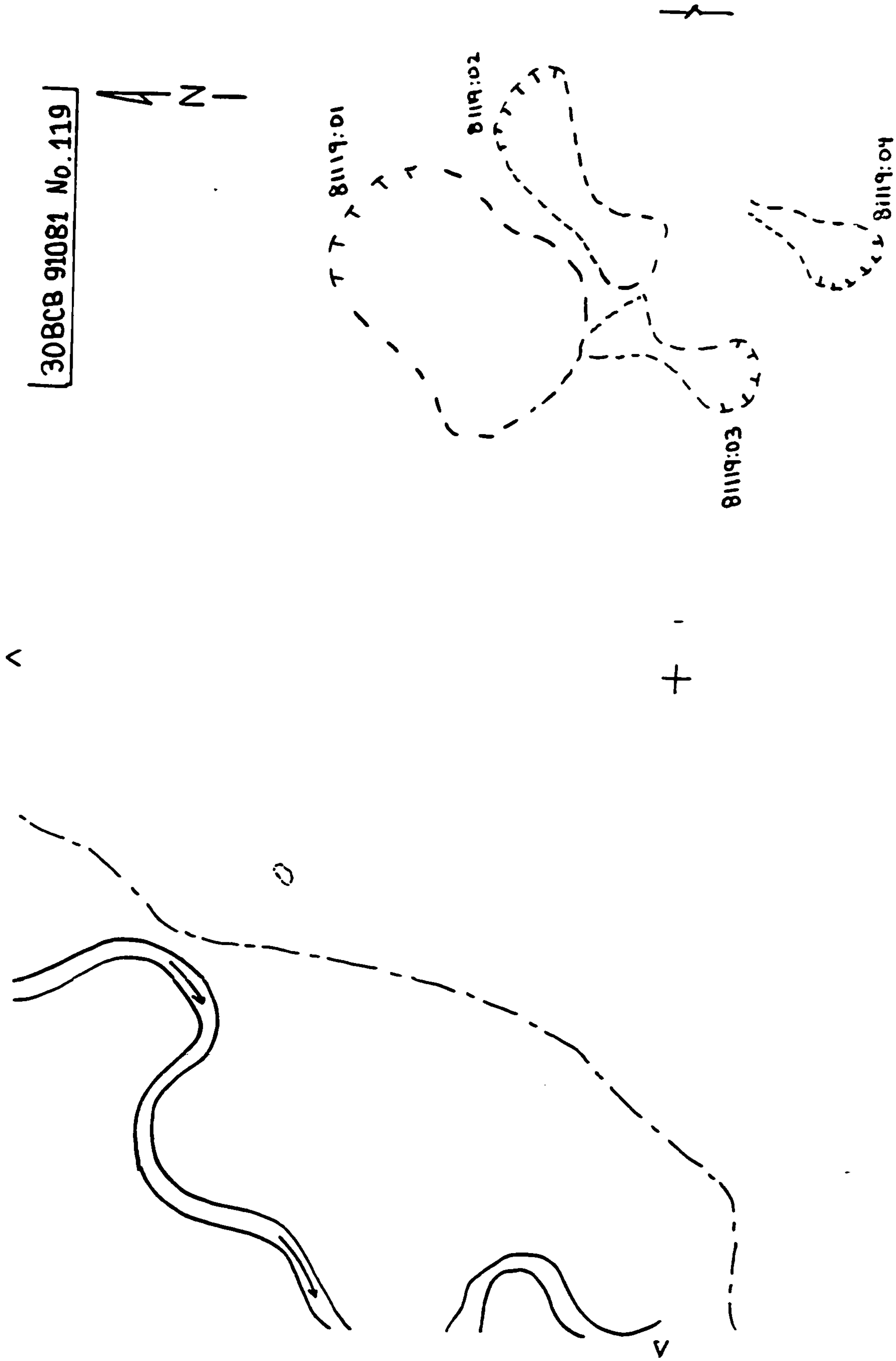
River (with direction of flow)

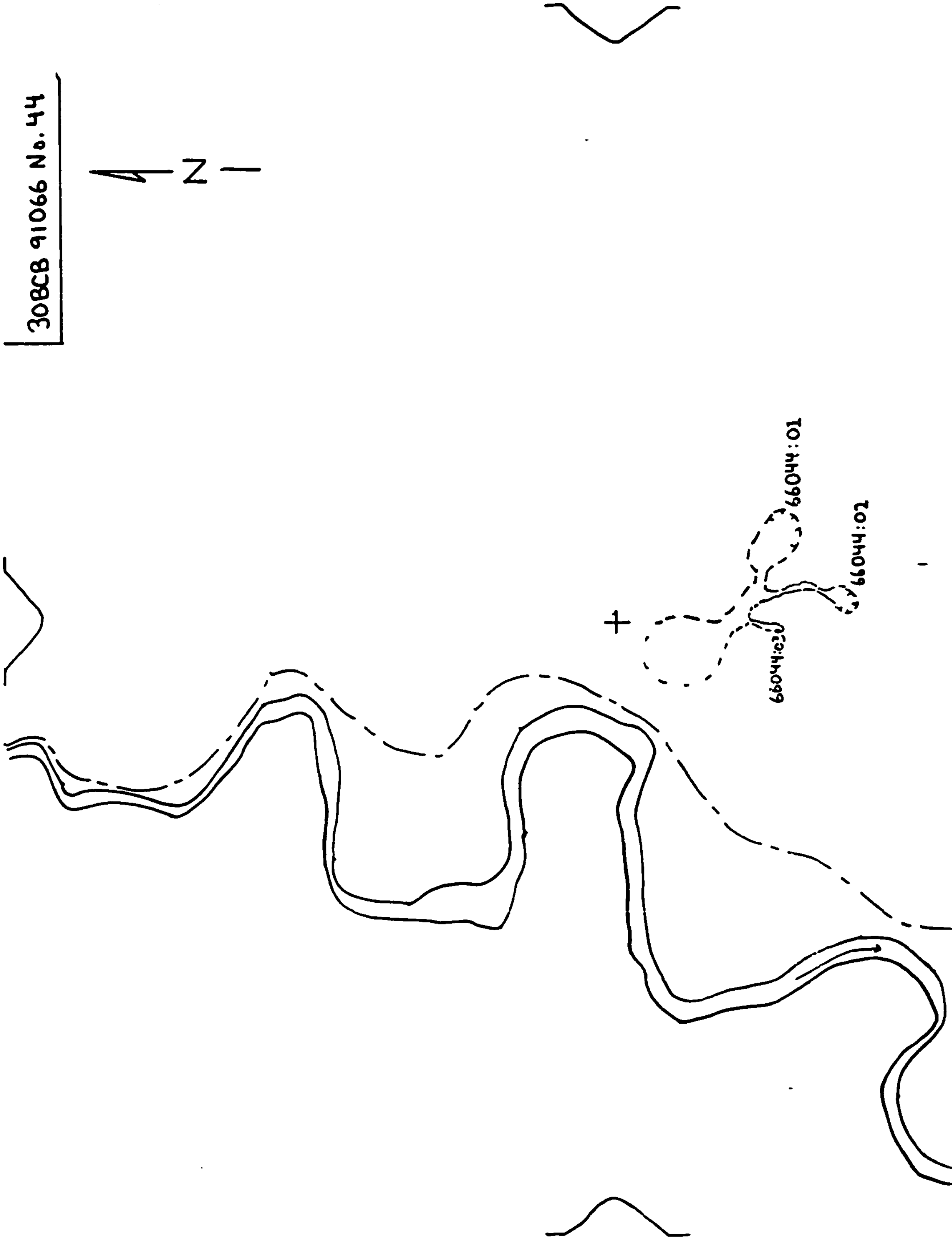
Mainline Forest Service Road

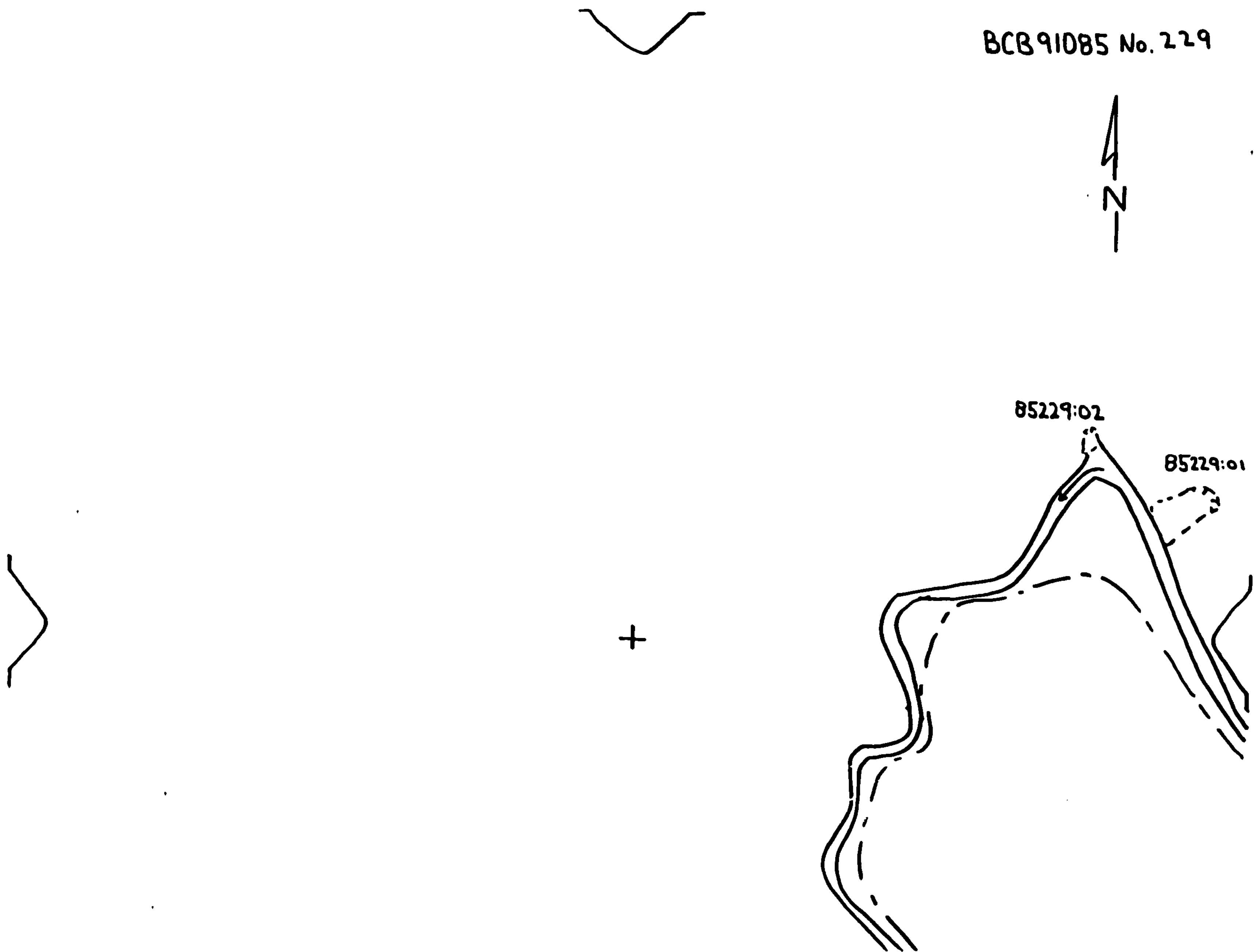
The figures in Appendix B have been copied from mylar overlays that I produced during the initial landslide inventory. The fiducial marks and principal point for each airphoto have been reproduced on each overlay so that features on the overlays can be located by placing a transparency of the overlays on the airphotos. The north arrows point to the top margins of the photos. Using the reference numbers showing on the airphoto overlays, the original airphotos can be purchased from the British Columbia Ministry of Environment Map Office, Maps B.C., in Victoria, B.C.

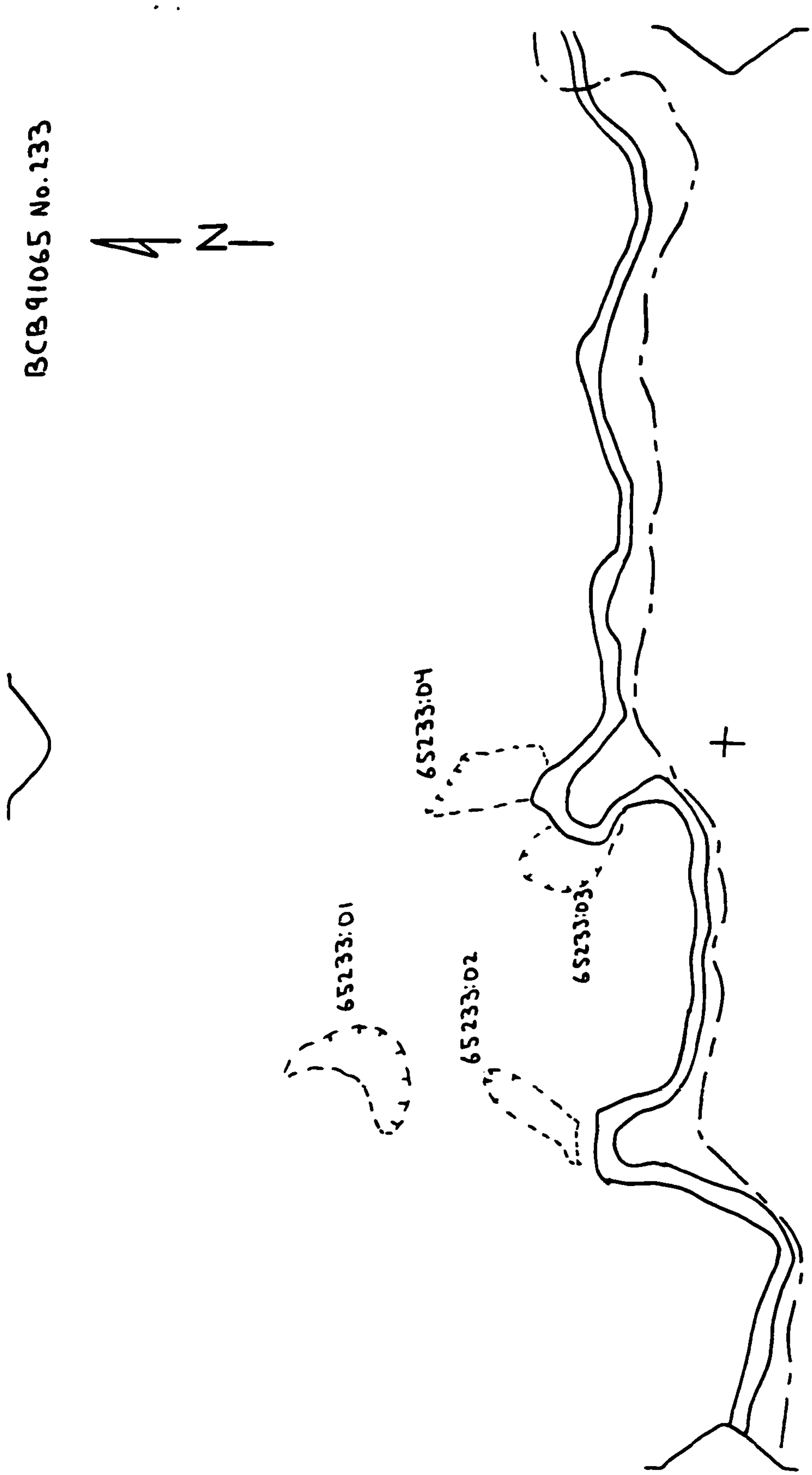

N
MORKILL RIVER
FRASER RIVER
8100B:01
8100B:02


30BCB91081 No.121
N
MORKILL RIVER

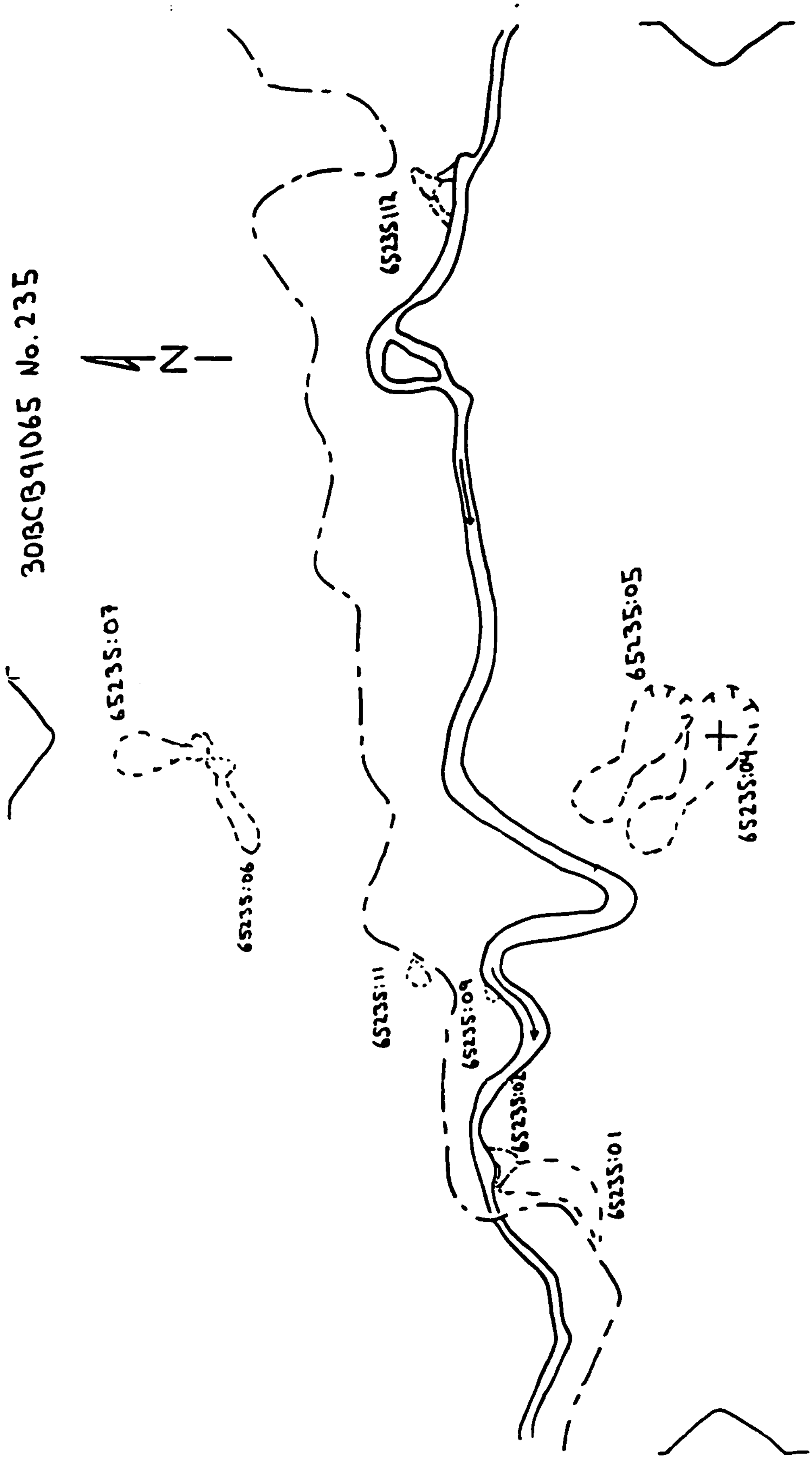

30BCB 91081 No. 119
N
8119:01
8119:02
8119:03
8119:04

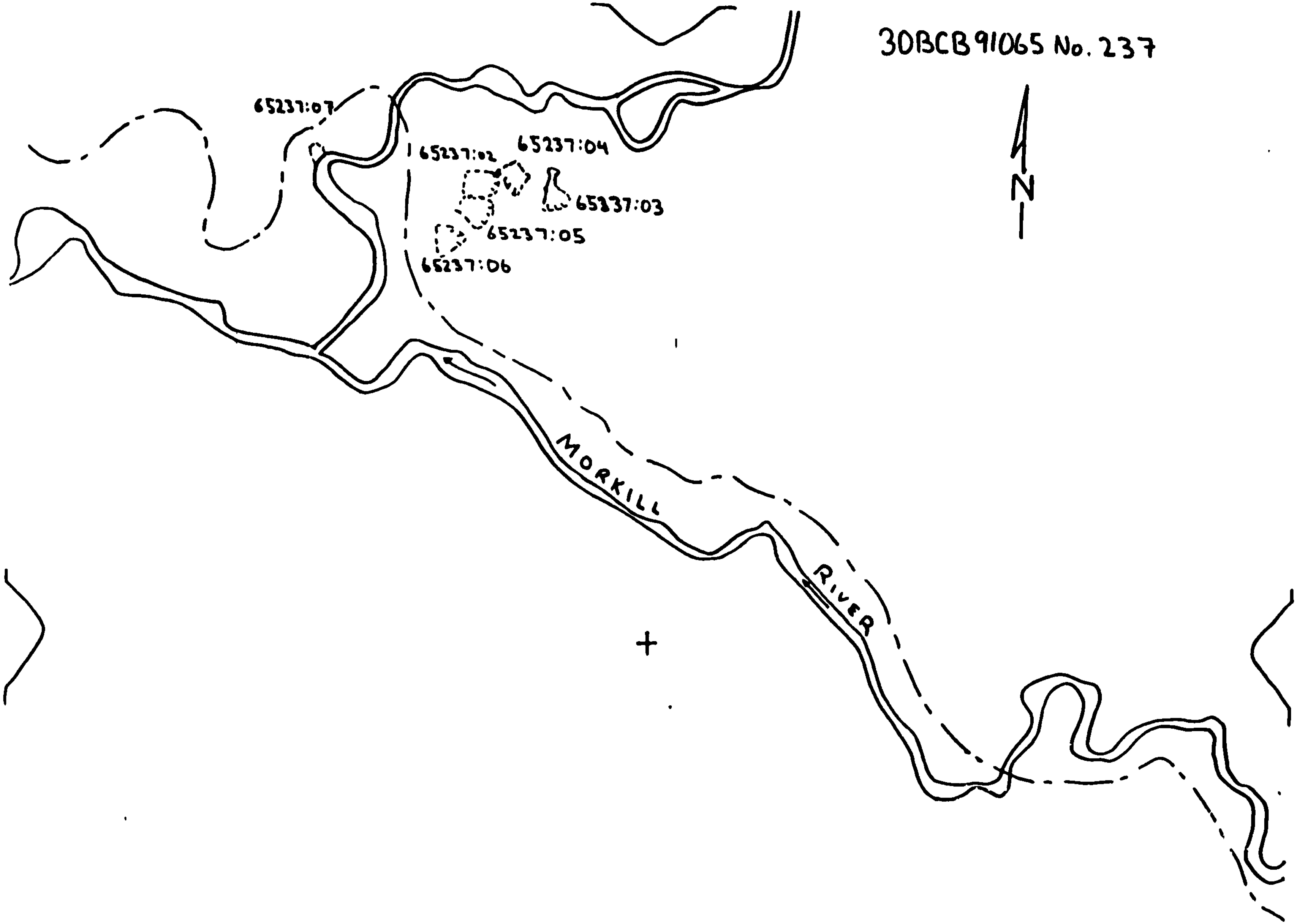

30BCB 91066 No. 44
N
66044:01
66044:02
66044:03

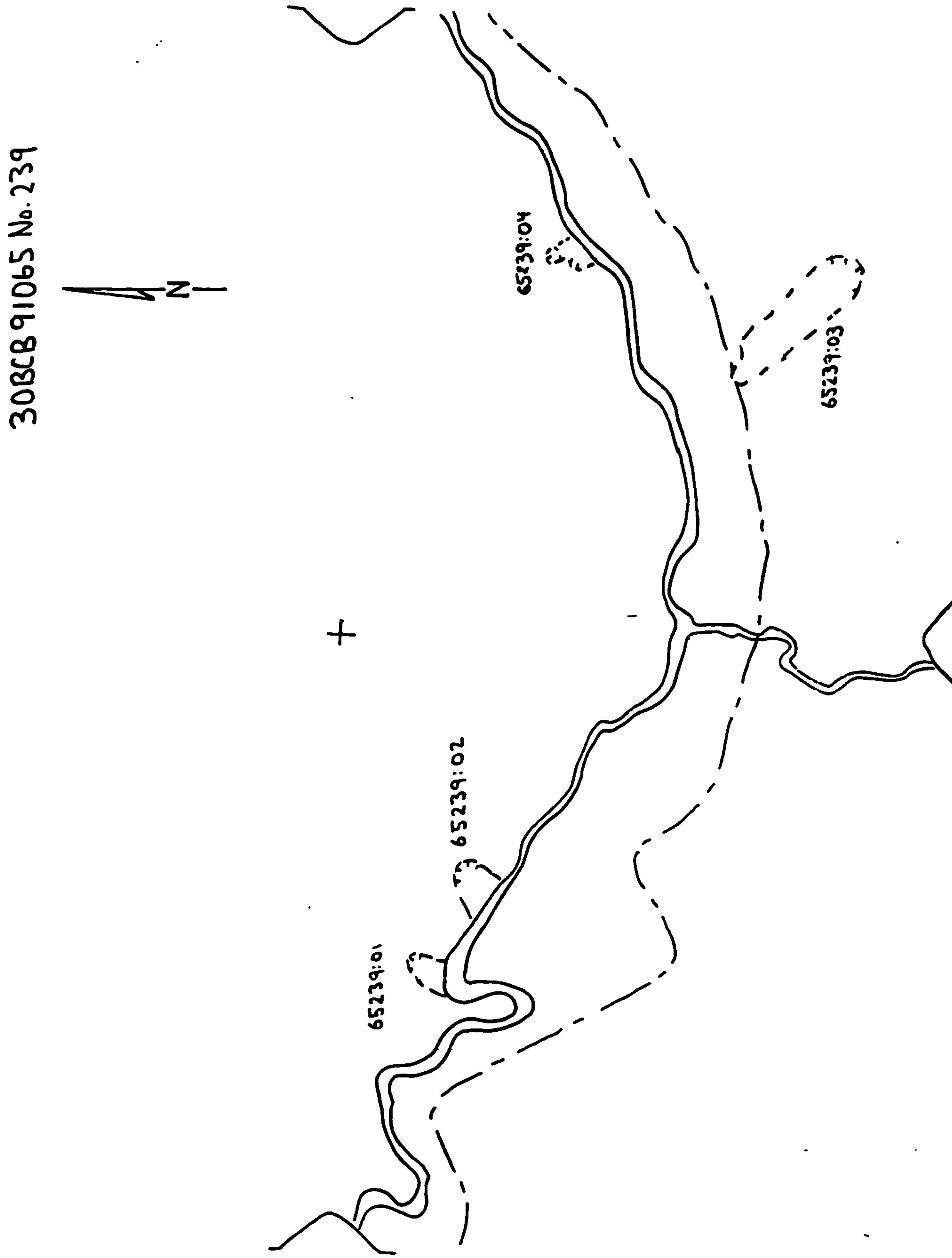

BCB91085 No. 229
N
85229:02
85229:01



BCB91065 No. 233
N
65233:04
65233:03
65233:01
65233:02


30BCB91065 No.235
N
6523S:12
6523S:07
6523S:06
6523S:05
6523S:04
6523S:11
6523S:09
6523S:02
6523S:01


30BCB91065 No. 237
N
65237:07
65237:02
65237:04
65837:03
65237:05
65237:06
MORKILL
RIVER



30BCB91065 No. 239
N
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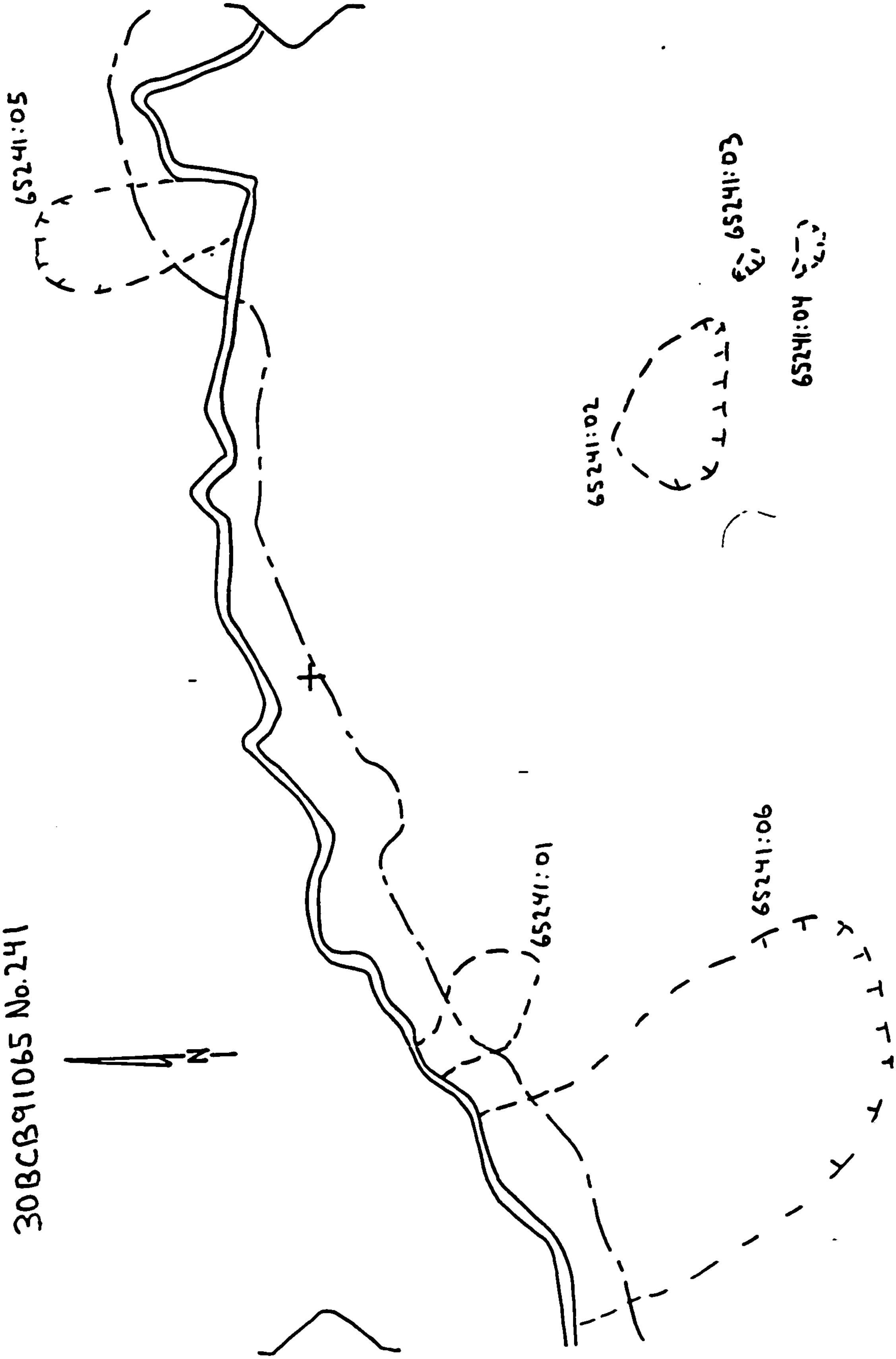
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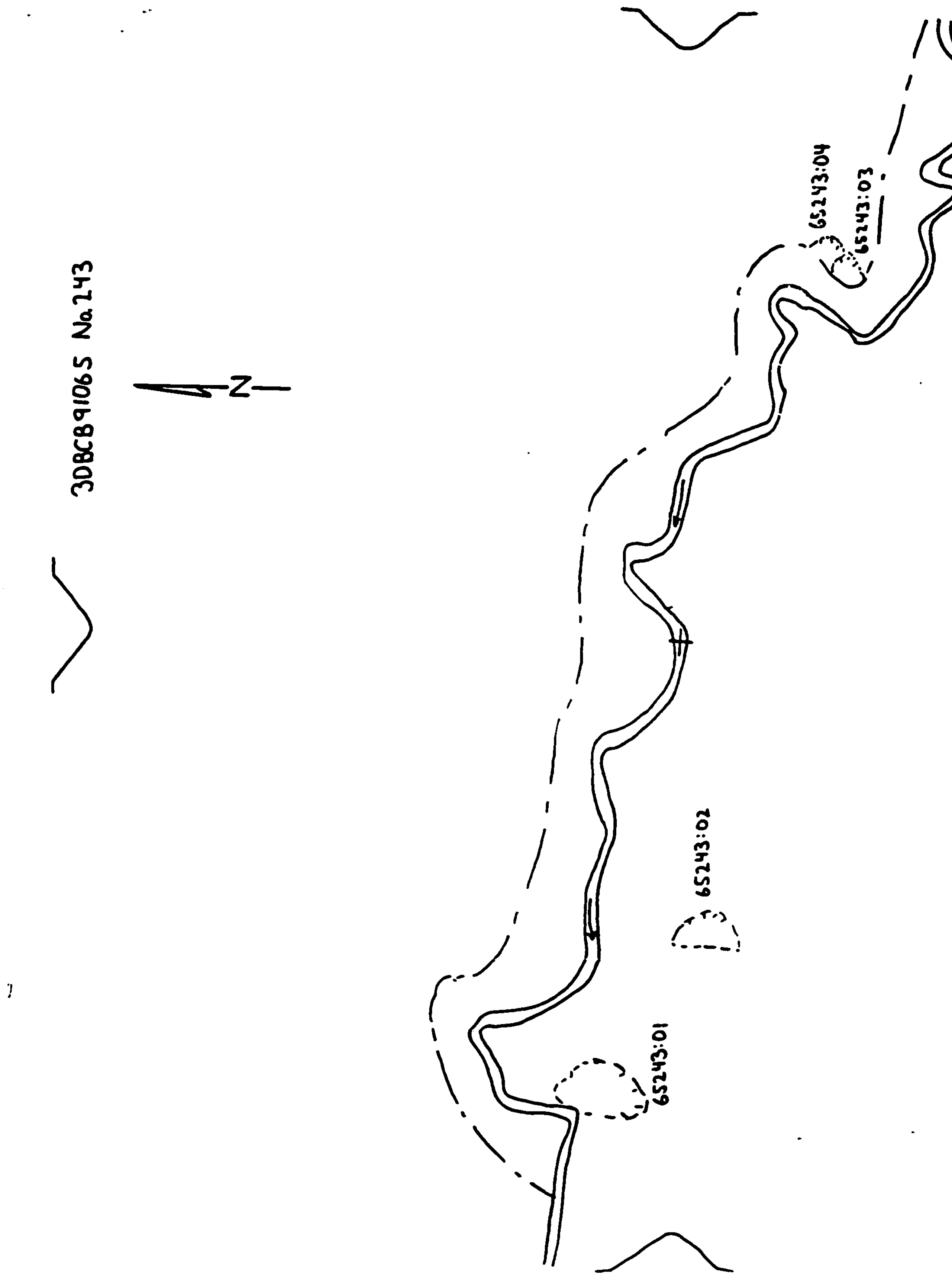
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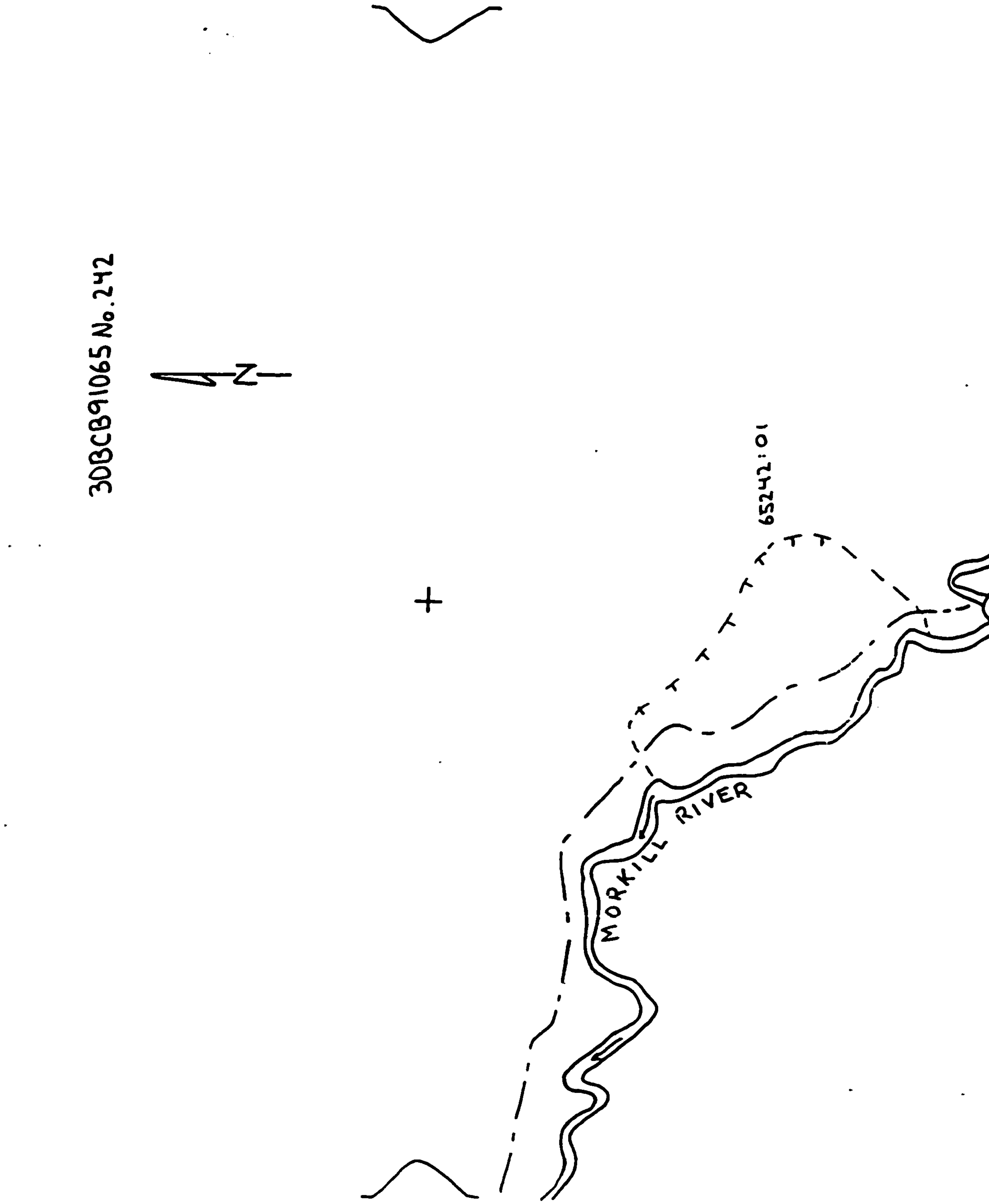
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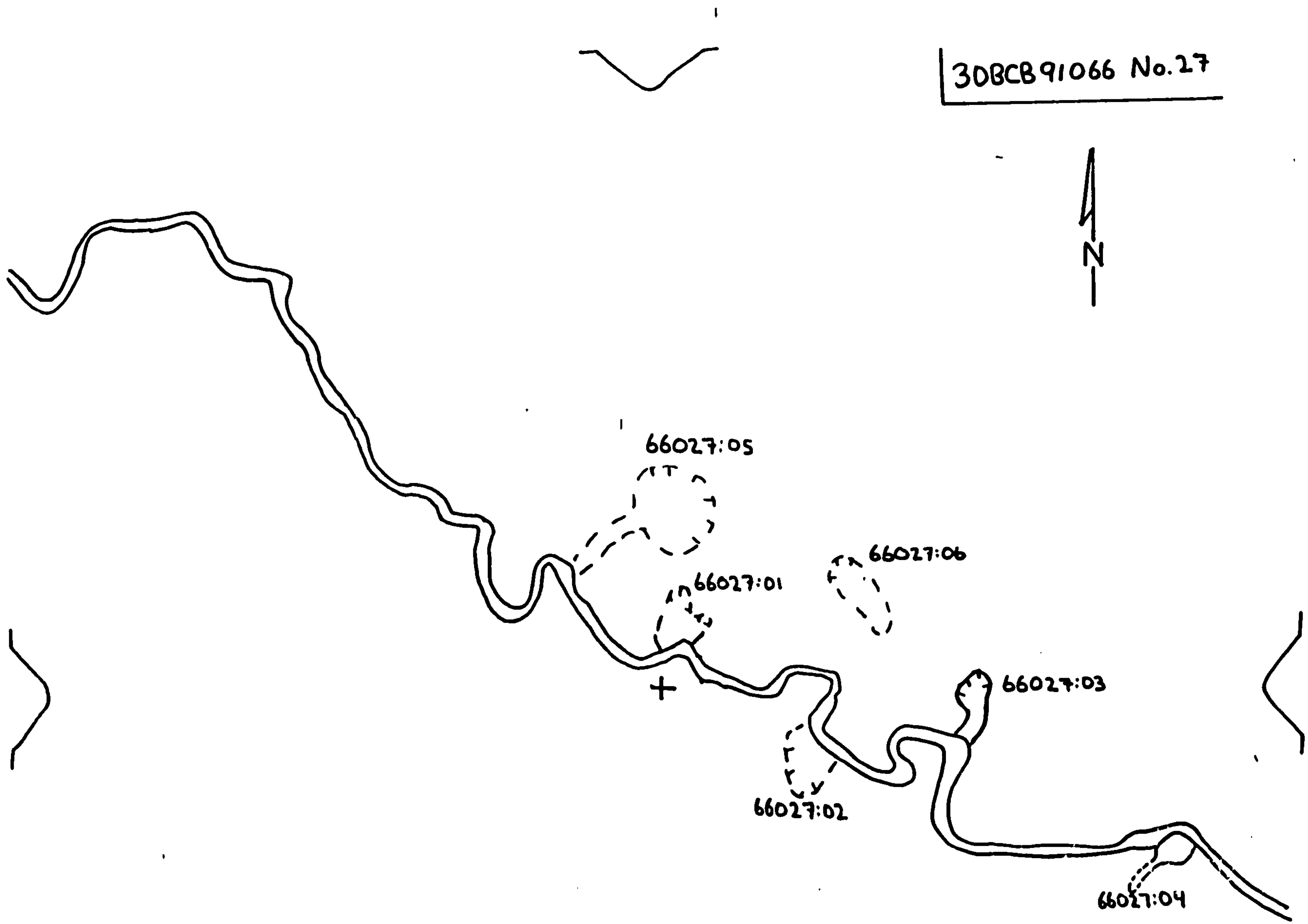
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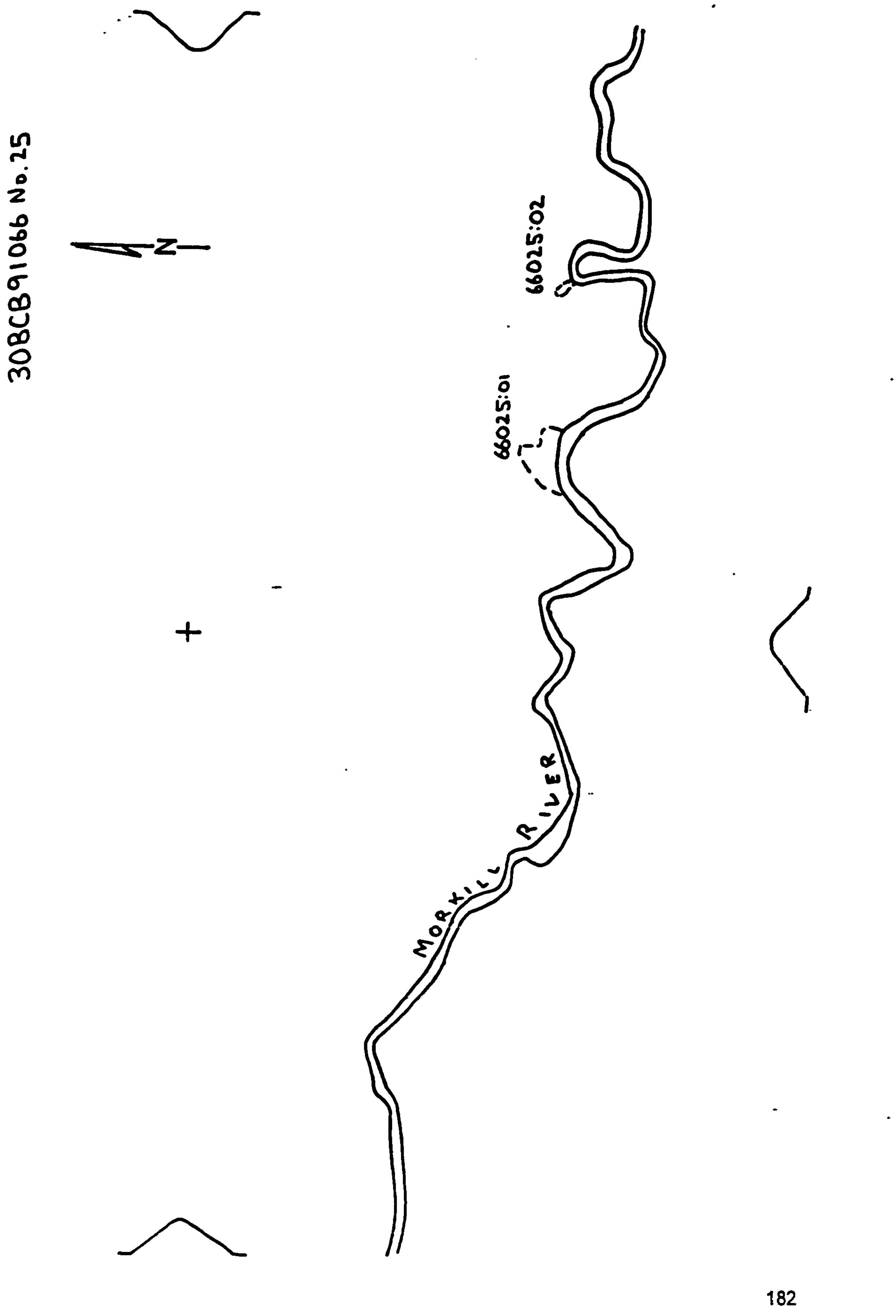
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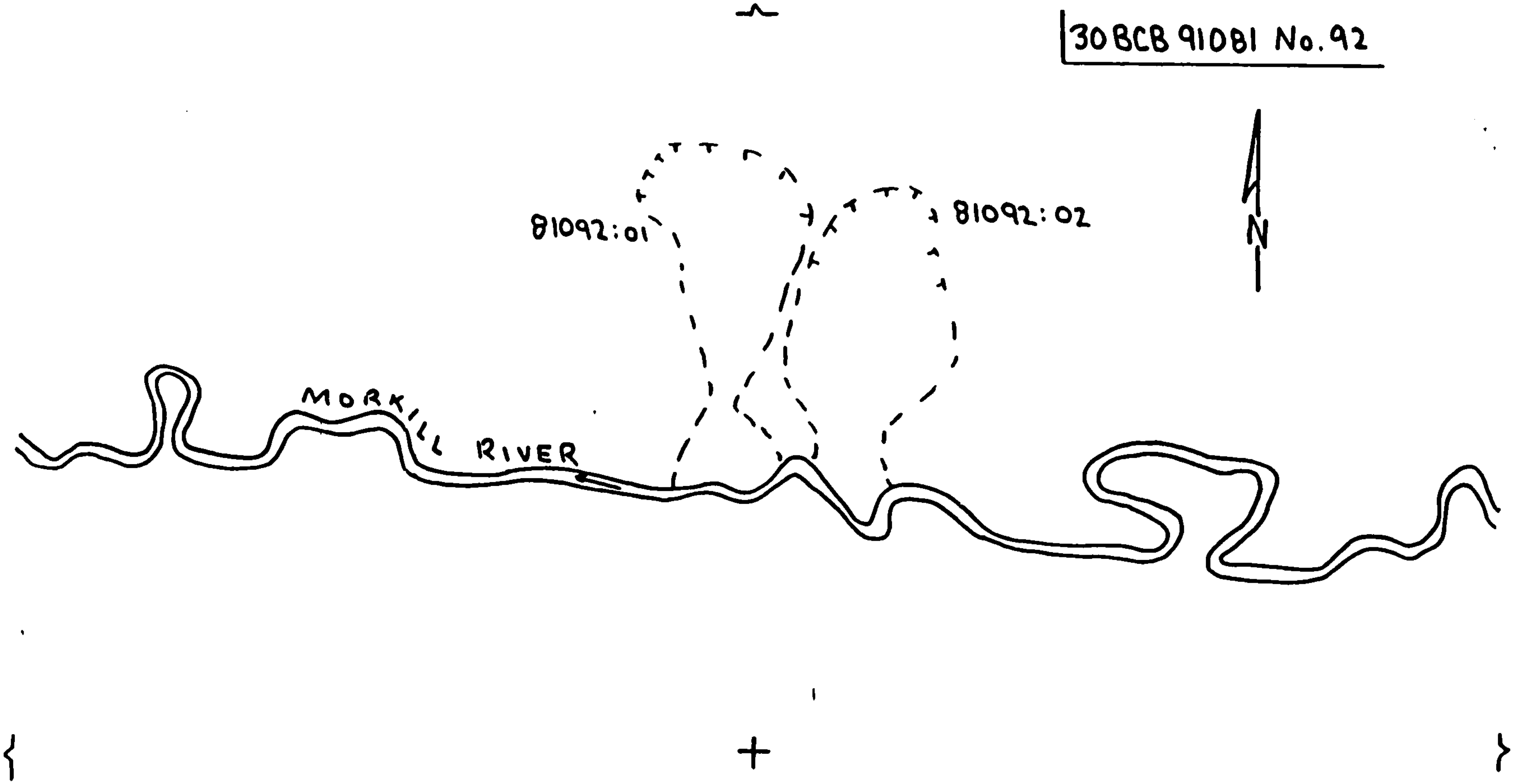
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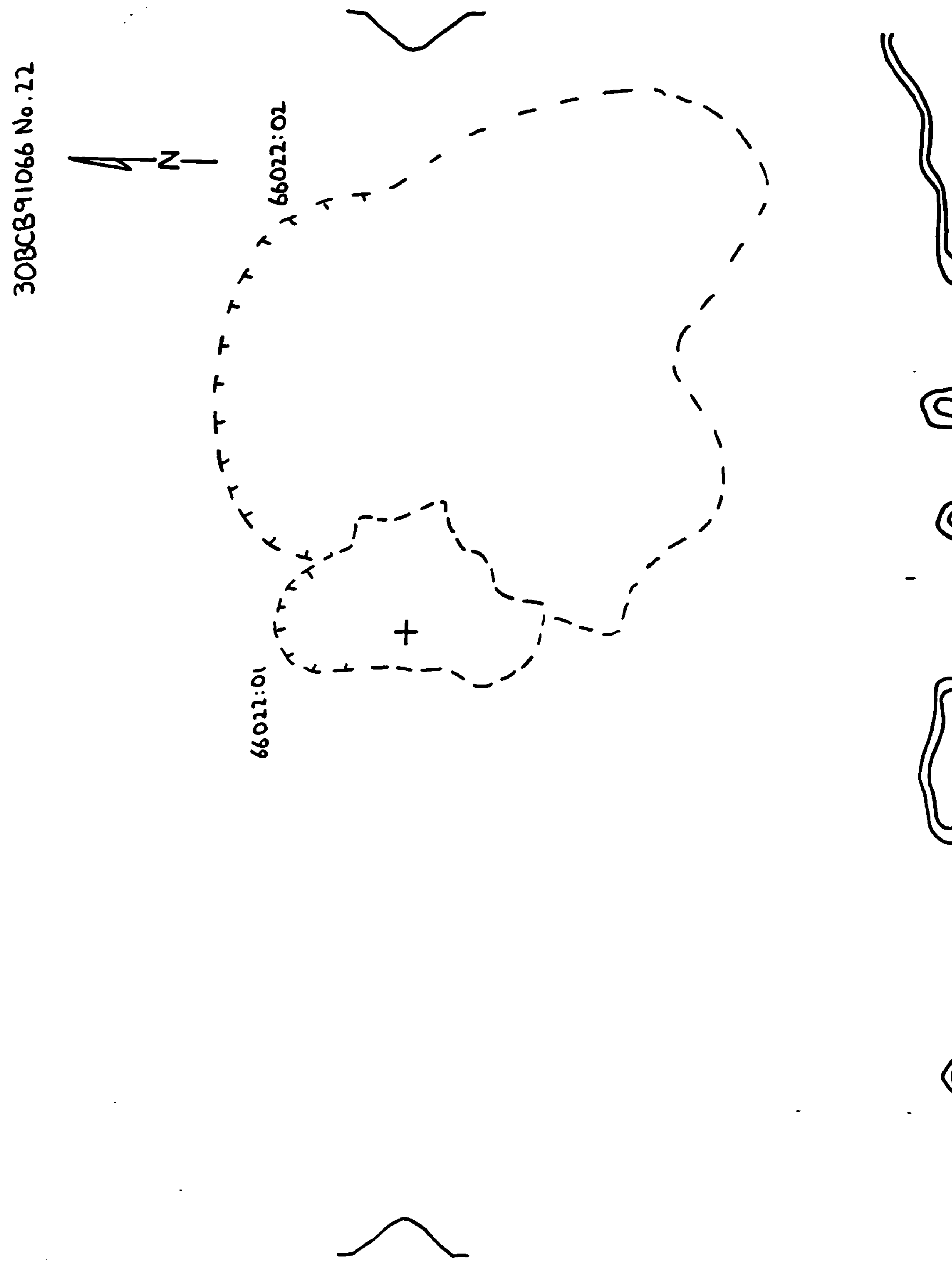
MORKILL RIVER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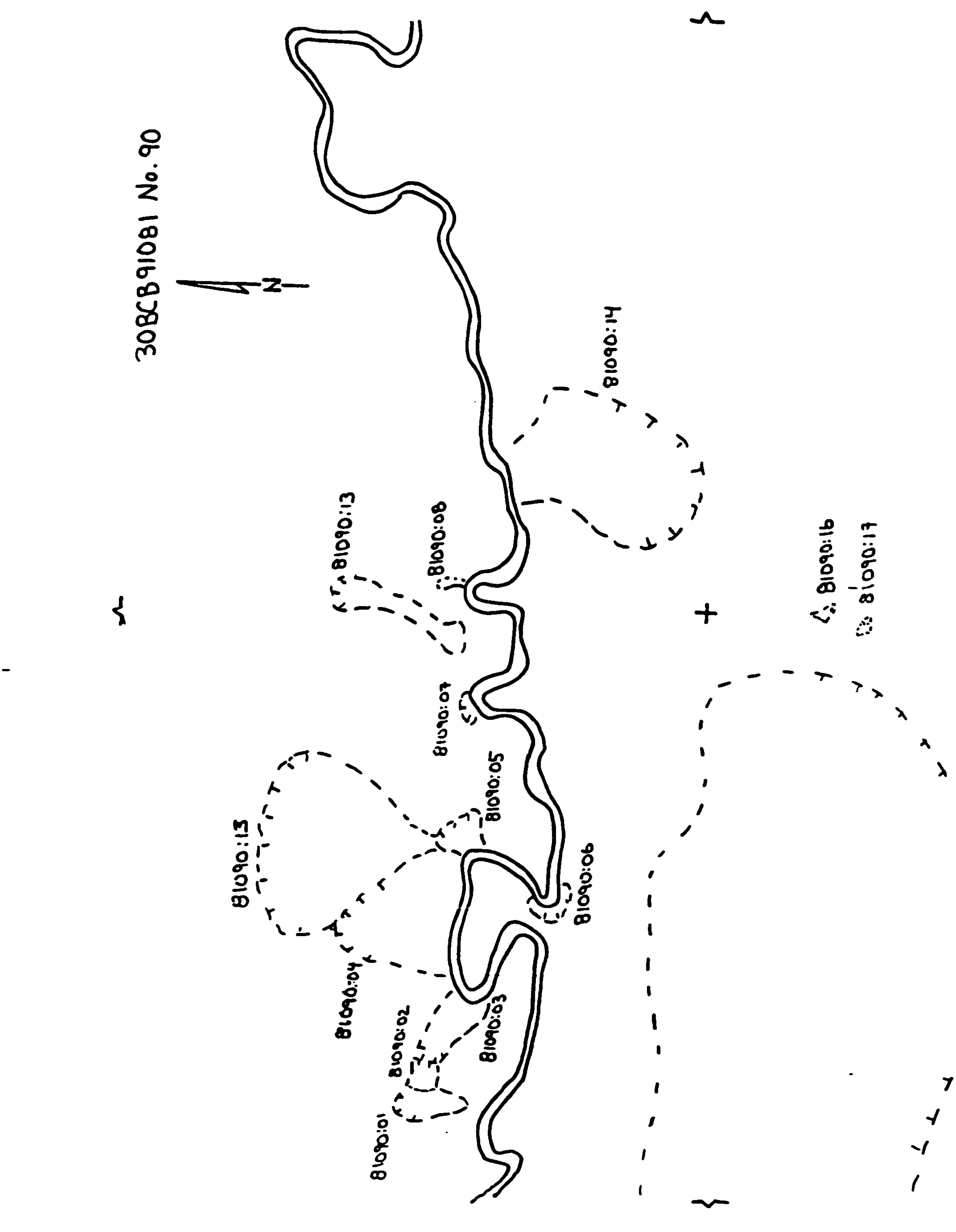
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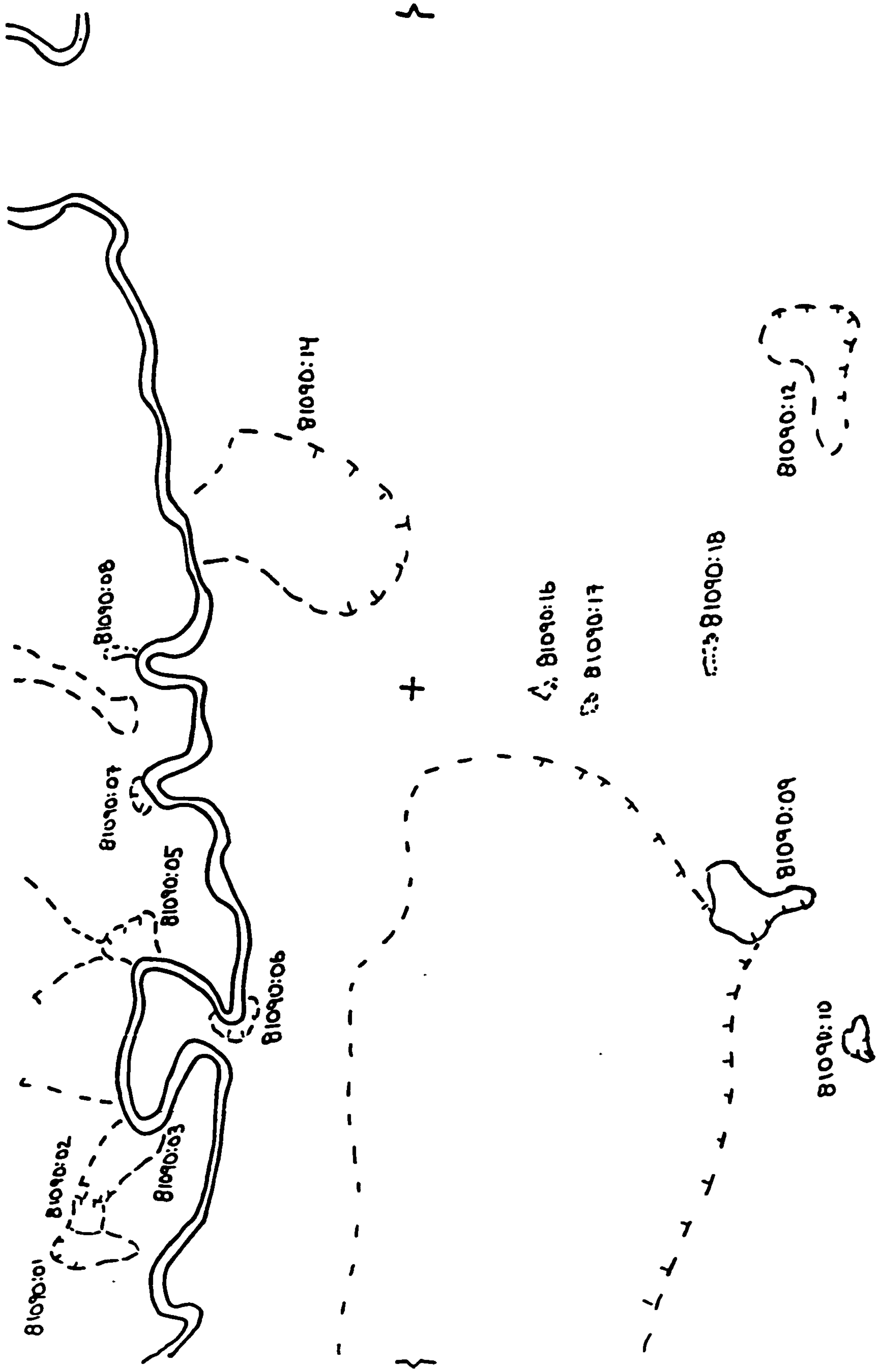
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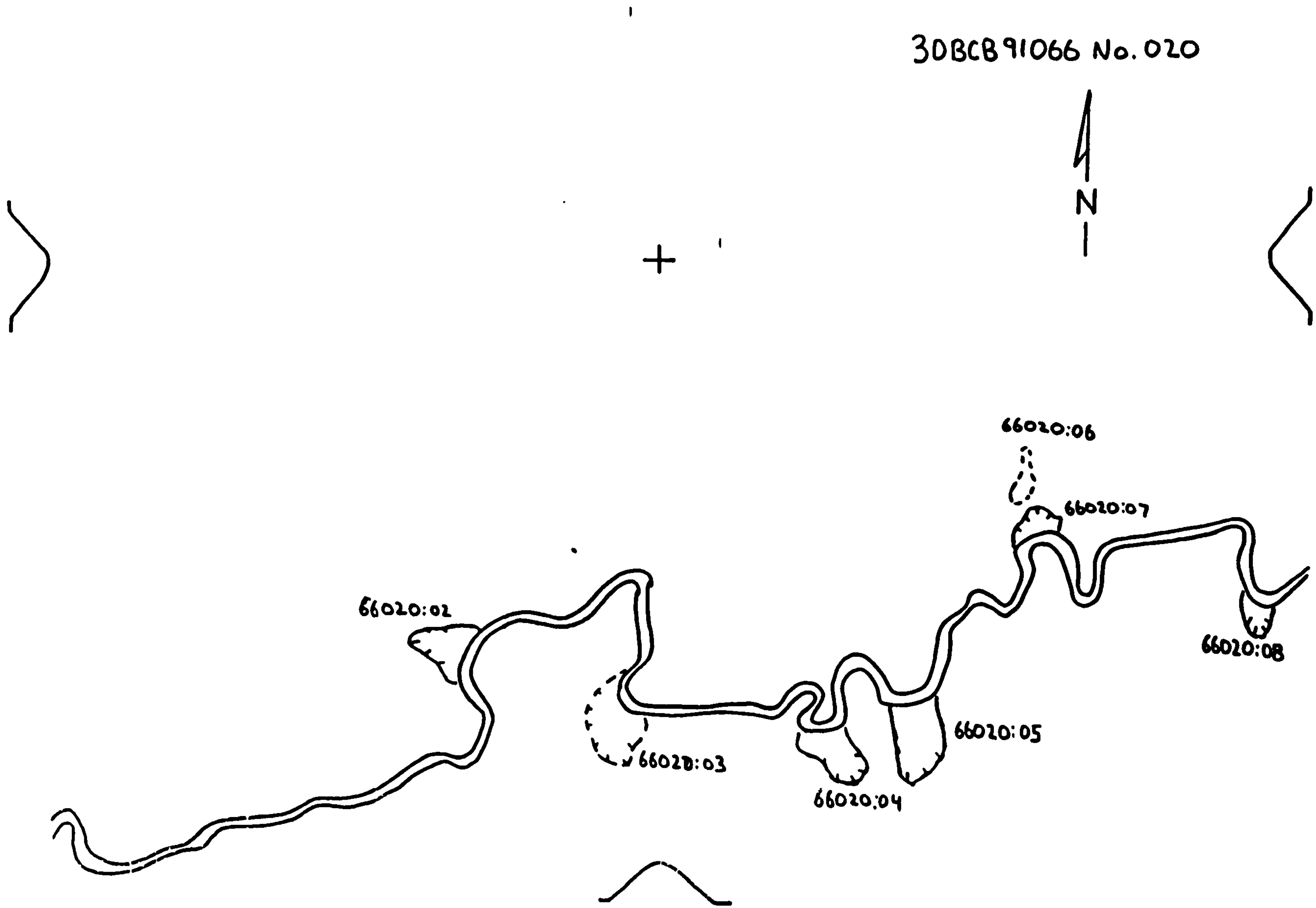
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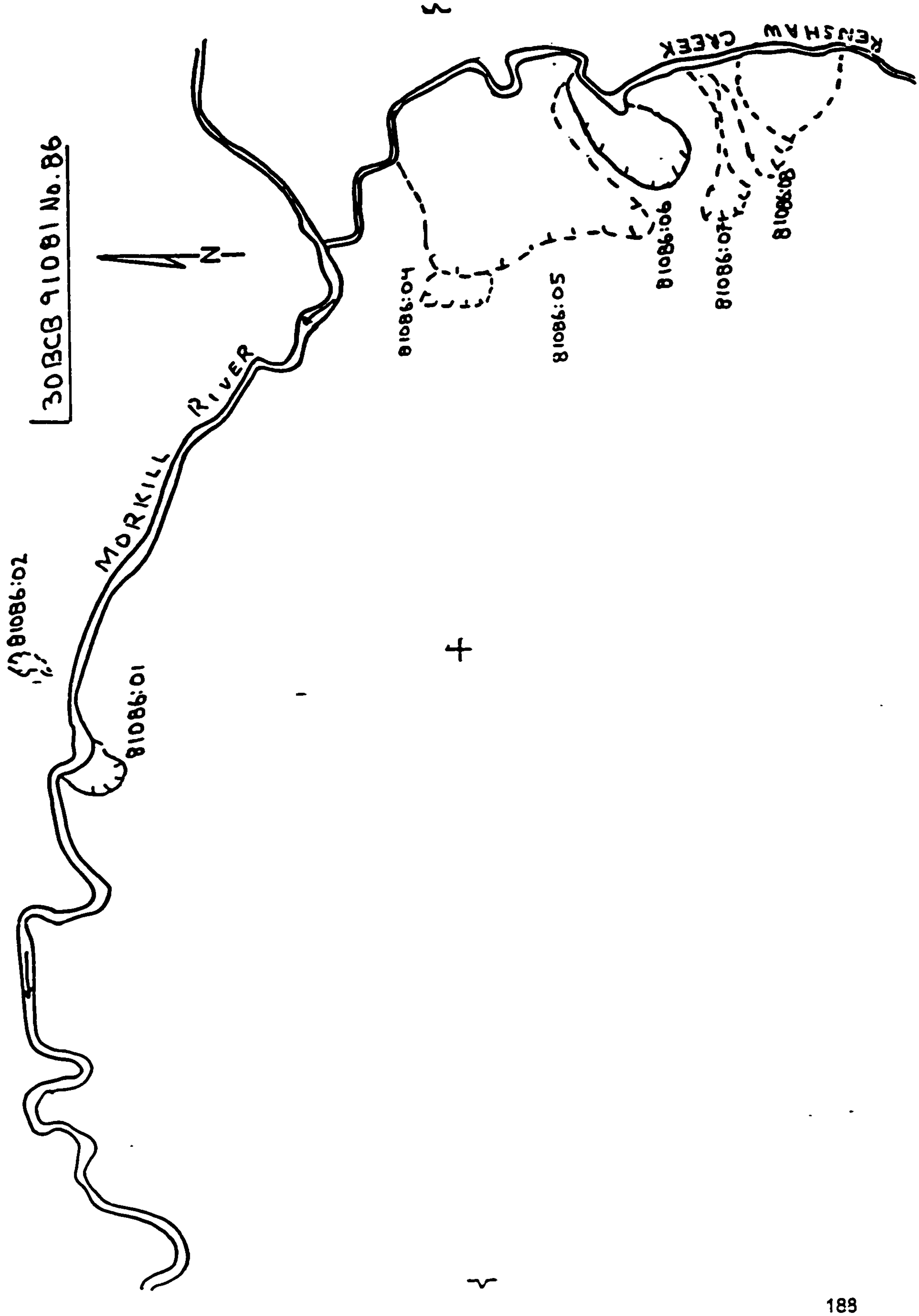
30BCB 91081 No.86
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MORKILL RIVER
KENSHAW CREEK
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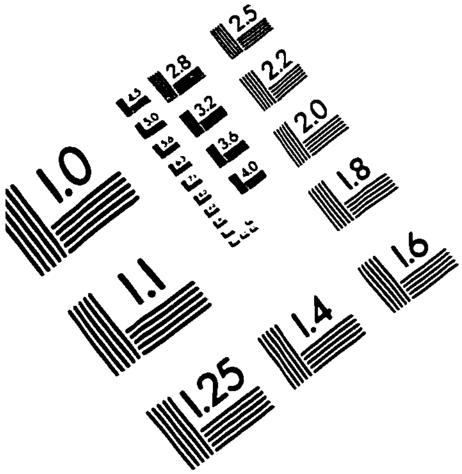
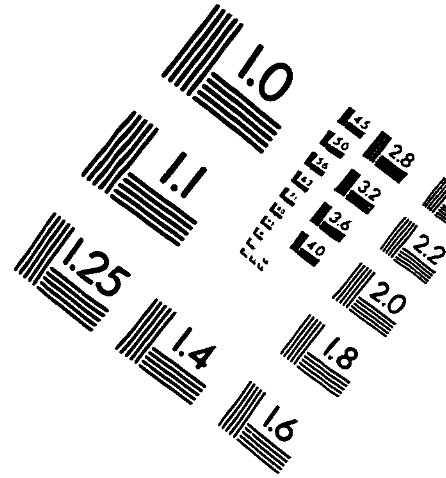
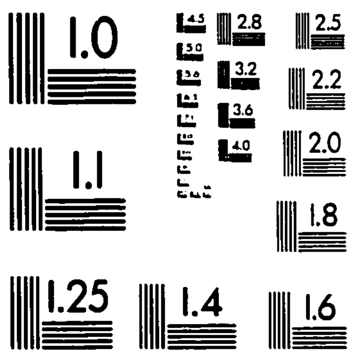
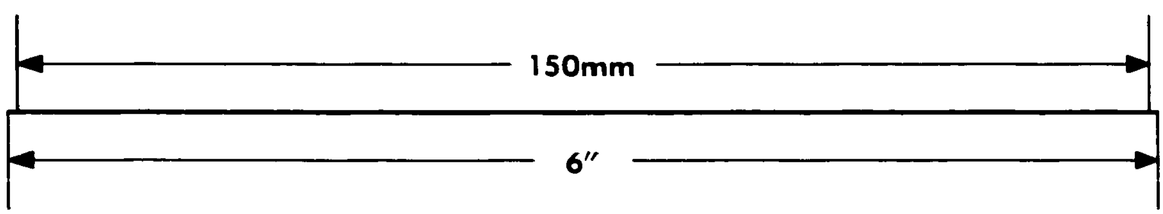
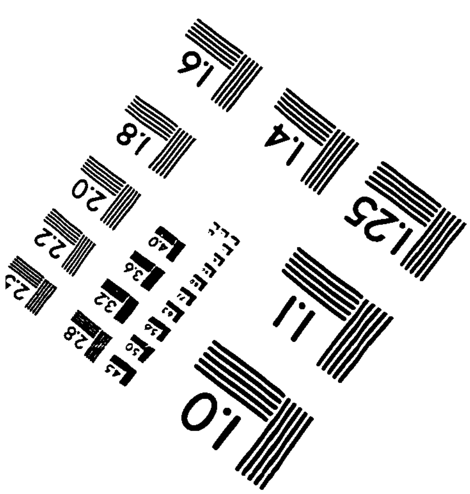
IMAGE EVALUATION
TEST TARGET (QA-3)

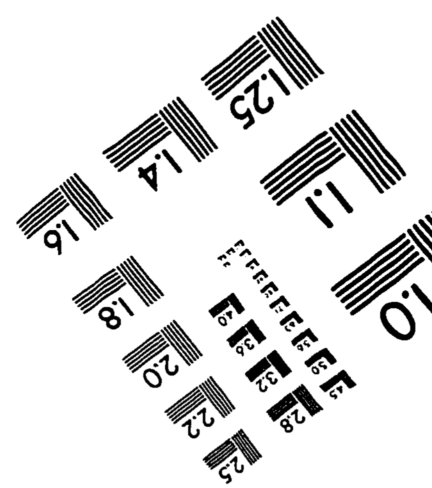












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