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Landslide incidence and its relationship with climate in three river valleys in the Bearpaw Formation in southern Alberta

By

Linheng Liang ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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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 **Landslide Incidence and its Relationship with Climate in Three River Valleys in the Bearpaw Formation in Southern Alberta** submitted by **Linheng Liang** in partial fulfillment of the requirements for the degree of the **Doctor of Philosophy.**

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Abstract

Landslide incidences on the Battle, Red Deer, and Bow Rivers were mapped in the Bearpaw Formation in southern Alberta, and the incidences on north- and south-facing slopes of the three river valleys were mapped as well. The results indicate that the incidences decrease from the Battle, to the Red Deer and to the Bow Rivers, and that incidences decrease from north-facing to south-facing slopes. Incidences on north facing slopes are significantly higher than on the south facing slopes on the Red Deer River and the Bow River.

Climate differences are regarded as the main cause of the difference in moisture conditions which in turn causes differences of landslide incidence among the three valleys since the valleys are in different climatic zones but have the same geological formation and similar postglacial histories. Differences in landslide incidence between north- and south-facing slopes are caused by microclimate. Microclimate is controlled mainly by direct short-wave radiation, which in turn controls potential evapotranspiration and Agro-Climatic Moisture Index (AgM Index) on differently facing slopes.

The moisture difference is further reflected in vegetation differences from one valley to another and from north-facing and south-facing slopes in the study area.

The vegetation characteristics of along different valleys and slopes of different aspect strongly support the moisture differences.

Slope angles under conditions of constant lithology are believed to be controlled mainly by moisture conditions. Average slope angles increase from the Battle valley, to the Red Deer and Bow valleys. Active slopes eroded by rivers are significantly steeper along the Bow River than along the Red Deer River. Abandoned slopes covered by colluvial materials along the three rivers are in a range 6.0 to 6.8°, which shows that materials along the three valleys involved in landsliding are similar.

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List of Symbols and Abbreviations

θ, latitude (^{0})

δ, solar declination (^{0})

φ_r, the soil friction angle (^{0})

α, β, slope angle (^{0})

c′, cohesion (*KN/m²*)

AgM Index, Agro-Climatic Moisture Index (mm)

D, diffuse ($MJ/m^2/Day$)

H, the hour angle of the Sun (^{0})

L, long-wave radiation ($MJ/m^2/Day$)

LI, landslide incidence (%)

N, number of days in month

N- and Sfc, north- and south-facing

Nfc, north-facing

P, precipitation (*mm*)

PE, potential evaportranspiration (*mm*)

Q*, energy balance ($MJ/m^2/Day$)

Q, extra-terrestrial solar radiation ($MJ/m^2/Day$)

Q_E, latent heat ($MJ/m^2/Day$)

Q_H, sensible heat ($MJ/m^2/Day$)

Q_n, flux density of short-wave radiation on the Nfc ($MJ/m^2/Day$)

Q_s, flux density of short-wave radiation on the Sfc ($MJ/m^2/Day$)

Q_{top}, solar radiation at the top of the atmosphere ($MJ/m^2/Day$)

S, solar constant, 1360 Wm^{-2}

Sfc, south-facing

Si, direct short-wave radiation or direct radiant flux density

S_{slope}, radiant flux density incident on slope ($MJ/m^2/Day$)

T_{max}, mean maximum and minimum temperatures (°*C*)

T_{min}, mean maximum and minimum temperatures (°*C*)

Z, zenith angle (°)

Chapter 1

Introduction

1.1 Background

Landslide activity has been studied extensively in the river valleys in southern Alberta either individually for a specific project or regionally to evaluate the slope stability. Landslide incidence, the percentage length of a valley wall involved in landsliding (Thomson and Morgenstern, 1977; Radbruch–Hall et al., 1982; Cruden et al., 1989) is used to quantify the stability of a river valley on a regional basis. The general conclusion from previous studies is that the incidence of landslides in southern Alberta increases from the south to the north. The main causes of the observed variation in the slope processes, in developments of a broad overview of the distribution of landslide activity, are lithology, climate, degree of weathering, groundwater conditions, vegetation cover, valley history, and toe erosion (Selby, 1970; Arvidson, 1972; Thomson and Morgenstern, 1977; Rib and Liang, 1978; Zaruba and Mencl, 1982; Cruden et al., 1991). While the effect of lithology has been well addressed, the role of climate has remained equivocal even though various studies indicate that it is one of the key factors affecting slope stability (Zaruba and Mencl, 1969, 1982; Crozier, 1986, chapter 5; Doornkamp, 1986, p.10).

Evidence of preferred slope aspects for landsliding on a regional scale in southern Alberta indicates that landslide incidence occurs predominantly on north-facing (Nfc) slopes (Arvidson, 1972; Beaty, 1972b; Cruden, et al., 1993). Beaty

(1972a) and Churchill (1981) consider that greater natural moisture accumulation and lesser insolation on Nfc slopes accounts for a higher landslide incidence in the semiarid southern plains of Alberta and South Dakota. Further study needs to be carried out to elucidate the role of climatic factors affecting landslide incidence especially when if geological conditions can be held approximately constant. Given the lithological homogeneity of the Bearpaw Formation in Alberta the region offers a good opportunity for assessing the separate role played by climatic conditions.

1.2 Rationale of the Relationship between Climate and Landslide incidence

Many factors can affect landslide incidence besides the major ones listed in section 1.1.1. These include tectonic effects, climatic changes, catastrophic events, or compound factors. As a consequence, the correlation and causation between climate and slope processes have never been simple, and is regarded by many researchers as problematical (Toy, 1977; Sauchyn, 1994; Campbell, 1997) especially in terms of spatial and temporal scales. Regardless of how complicated the interaction between climate and slope processes is, its role in molding the earth's landforms cannot be ignored. Climate acts as an important agent on various aspects of nature, and on the magnitude and frequency of natural processes (Tricart and Cailleux, 1972; Sugden, 1973; Doornkamp, 1986, p.10). Studies have also shown a strong relationship between climatic factors and slope processes (Beaty, 1972; Tricart and Cailleux, 1972; Toy, 1977; Churchill, 1981; Budel, 1982).

Well-controlled studies are necessary to minimize the effects of factors such as geologic conditions, and valley history, to further elucidate the relations between climatic factors and slope processes. Similar sites in the same or similar geological settings tend to show similar responses to a particular factor or stimulus, while different climates could leave different imprints on landforms due to the different rates of the processes operating on these same geological settings. This is the key point in the study of the relationship between climate and landslide incidence in this thesis.

Previous studies indicate that climate acts as an important agent on various aspects of nature, and on the magnitude and frequency of natural processes, such as the ecosystem, energy and natural resources, and engineering projects (Doornkamp, 1986, p.10). The different strengths of the agents acting on different regions can be defined as climatic zones and lead to the classification of climates. Climate changes over time and distance are coupled with differing magnitudes and rates of slope processes in different climatic zones. In the study area, the slope processes that concern us have been active since the retreat of the Pleistocene glaciers. Campbell and Campbell (1997) have identified a "period of instability" from 10,000-0 ^{14}C cal yr B.P., and in this time period, climatic change is relatively minor and has shown a trend toward wetter climate. It is understandable that smaller variations are going on at the same time as a major trend is occurring (Hare and Thomas, 1979).

For different sites with the same or similar geological settings in different climatic zones across the study area, the magnitudes and rates of slope processes should be different because climatic factors act on the sites with differing strengths. The difference of climates from north to south in the study area probably existed during the period of instability (Campbell and Campbell, 1997; A. Bush, 1998, pers. comm.). Minor climatic changes would not diminish north-to-south climatic differences which are controlled by latitude, and the solar constant, by regional topography and by meteorological factors, such as air stream and oceanographic influences (Phillips, 1990). The northern part of the study area (long: 111° 33', lat: 52° 22') is strongly influenced by the precipitation from the Rocky Mountains, which represents a specific climatic zone and ecoregion (Longley, 1972; Strong and Leggat, 1992). Due to specific topographic control, higher frequencies of storms initiated from around the Rocky Mountain House area move in a northeastern direction and cause increased precipitation in the northern part of the study area (Longley, 1967; Environment Canada, 1987; Philips, 1990; G. Reuter, 1998, pers. comm.).

Climatic change since the last deglaciation might have had an impact on the precipitation in the study area, but probably has not changed the gradient of the precipitation over comparatively short north-south distances in the study area because the topographic control of the Rocky Mountains has remained constant (A. Bush, 1998, per. comm.). Thus, the northern part of the study area would likely be wetter than the southern part of the study area during the landscape instability event (Campbell and Campbell, 1997). The differences of climates across the study area are represented by different climatic zones and vegetation (Longley, 1972; Strong and Leggat, 1992) in which the mapped landslide incidences differ (Chapter 2).

We assume that astronomical and topographical factors dictate that the northern part of the study area is cooler and wetter than the southern part. Climatic records taken since the late 1880s have shown that the northern part of the study area has higher precipitation and lower temperature than the southern part (Longley, 1972). This study therefore investigates the role of climatic factors in the differences of landslide incidences from one river area to another, as well as in the differences between N- and Sfc slopes.

For slope processes operating within postglacial time, the magnitude of climatic change is probably quite small in comparison with the range of present regional climates (Campbell and Campbell, 1997). Calibration of radiocarbon dates of postglacial geomorphic events in southeastern Alberta shows that the interval of landscape instability is ca. 10,000-0 cal yr B.P. (Campbell and Campbell, 1997). Site-specific studies show that the increase of growing temperature is 1.5-3°C from 9990-3160 cal yr B.P in central Alberta (Vance and Wolfe, 1996), and the increase of annual precipitation prior to 6860-6800 cal yr B.P. is about 65 mm (Zoltai and Vitt, 1990). The sporadic data do not cover the whole period of postglacial history but they show a similarity between past and present climates, and they also indicate that the magnitude of climatic change is limited. The driest period may be the landscape stability interval, ca. 12,000-10,000 cal yr B.P (Campbell and Campbell, 1997). The general trends of climatic change since deglaciation are a gradual increase of moisture and increase of temperature. However, the spatial variation in precipitation from the Battle River to the Red Deer River across the study area is about 108 mm (from 1980 to 1990) during summer time (Chapter 3). The average difference of annual precipitation from the Aspen Parkland to Dry Mixed Grass ecoregions across the study area is 140 mm and the temperature difference is 2.0 °C from 1979 to 1989 (Strong and Leggat, 1992).

Considering the small magnitude of climatic change during the landscape instability interval in which landslides have been taking place, it is possible to apply modern climatic records in terms of the difference of climates among the sites, not as absolute values. Assuming that present differences in climate that have been operating on these same geological settings in different climatic zones in southern Alberta have changed only little during the Holocene, it is reasonable to investigate the relationships between differences of climate and differences of landslide incidence from sites to sites across different climatic within the same geologic setting zones in the study area. This thesis focuses on differences of climate across the study area as well as the difference of microclimate between N- and Sfc slopes. The observed differences in slope processes result from the differences in the climates operating at different sites based on similar climatic differences through postglacial time at these different sites.

The above background forms the foundation on which to model the direct short-wave radiation, evapotranspiration and Agro-Climatic Moisture Index on Nfc and Sfc slopes on the Battle River and the Red Deer River, and on the right and left banks of the Bow River in the Bearpaw Formation. The modelling results can be supported by differences in vegetation distribution and their characteristics on the Nfc and Sfc slopes in the study area, as well as from one river section to another.

1.3 Thesis Objectives

The purpose of this thesis is to investigate the differences in landslide incidence on slopes of contrasting aspect and within different climatic zones. The specific objectives are:

a) To investigate the difference of landslide incidences on N- and Sfc slopes in different climatic zones.

b) To document all landslides in the study area and to calculate and statistically test for differences in landslide incidence as a function of slope aspect and climate (Chapter 2.2, 2.3 and 2.4).

c) To model direct short-wave radiation, evapotranspiration, and AgroMet Moisture Index (Strong and Leggat, 1992) on N- and Sfc slopes based on average slope angles and aspects. Direct short-wave radiation was modelled because direct short-wave radiation is the direct cause of different soil moisture conditions, and different moisture condition plays a key role in landslide activities.

d) To investigate and map vegetation on N- and Sfc slopes along valley walls of each river as well as the general differences in vegetation cover between river basins since vegetation is an indicator of the moisture conditions (Chapter 4.2 and 4.3).

e) To measure slope angles on N- and Sfc slopes along the three rivers since different soil moisture conditions affect steepness of slopes by decreasing effective stress. Asymmetrical slope profiles may be caused by different moisture conditions. Other factors such as river meanders, bedding orientation, and groundwater, are discussed as well (Chapter 4.4, 4.5 and 4.6).

1.4 Rationale of the selection of study area

The geological boundaries in the study area have specific south-north geological alignments (Carlson, 1970), while the climatic classification has a major east-west boundary line separating the Aspen Parkland and Grassland climatic zones (Strong and Leggat, 1992). Another climatic line separates the Grassland into two subclimatic zones, Mixed Grass and Dry Mixed Grass Ecoregions (Strong and Leggat, 1992) crossing the study area from SW to NE. Based on the geotechnical properties of the geological units in southern Alberta, the Bearpaw Formation was chosen as the sample unit because of its very weak geotechnical properties. Based on the above criteria, the study area was finally chosen as Long: 111-113.5° W and Lat: 50.5-53.3° N (Figure 1.1 after Green's map (1972)) to provide adequate geological and climatic contrasts. The alignments of the climatic and geological boundary lines, approximately perpendicular to each other in the study area, greatly facilitates the study of the relationship between climate and landslide incidence in the same geological formation.

Another factor influencing selection of the study area is fact that the river valleys are not preglacial channels. This permits a comparison of landslide incidence between the three river basins in the same geological formation within a consistent pattern of fluvial dissection of the Plains where landsliding of valley sides have been the dominant Quaternary geomorphic processes in southern Alberta and Saskatchewan (Goulden and Sauchyn, 1986).

Glacial and postglacial deposits (underlain by more or less horizontal bedrock) constitute the surficial deposits in the study area (Beaty and Young, 1975, Ch.5). The river valleys studied are dominantly postglacial valleys. In each case, the valleys appear to have been initiated by meltwater from the late Wisconsinan glaciation and to have been subsequently modified. The study area belongs to the Plains Region physiographic unit, and has a surficial expression of "endless plains" based on Beaty and Young's (1975) description. The presence or absence of relict landslides is an important geomorphological characteristic to be considered in the landslide zonation since many landslides are due to reactivation of old landslides (Varnes, 1978).

The major climatic boundary is also the boundary between dry grassland to the south and relatively humid forest to the north (Hare and Thomas, 1979). This boundary, consistent with that defined by Strong and Leggat (1992), separates areas "characterized by a distinctive regional climate as expressed by vegetation" (Subcommittee on Biophysical Land Classification, 1969).

1.5 Study Area

1.5.1 Physiography

The study area lies within an area where the Battle River, Red Deer River and Bow River cross the Bearpaw Formation (Fig. 1.1). The area belongs to the Alberta Plains (Drinkwater, et al., 1969), and is characterized by flat to undulating surfaces. The average elevation on is about 750m in the Battle River and Bow River areas, and 870m in the Red Deer area . All three rivers generally flow from WNW to ESE to cross the study area.

1.5.2 Geology

Bedrock geology of the study area has been documented in many geological reports and maps (Russell and Lands, 1940; Allan and Sanderson, 1945; Green, 1972;). The bedrock that crops out along the three river valleys is Upper Cretacous in age and consists of sedimentary rocks deposited in marine, marginal marine and continental environments (Williams and Burk, 1964). Three geological formations are involved (Figure 1.1). Where the Bearpaw Formation starts to intersect the river valleys at the west margin of the study area, the Bearpaw Formation is overlain by the Horseshoe Canyon Formation. In the north of the study area, the Belly River Formation underlies the Bearpaw Formation. The latter is predominantly a flat lying shale and siltstone interbedded with bentonites. The shale unit of the Bearpaw Formation dominates the entire study area, and is considered to control landslide incidence due to its very weak geotechnical properties (Thomson and Morgenstern, 1977; Cruden, et al., 1995). Tectonic forces have not significantly deformed these units; the area is not seismically active at present (Fulton, 1989), and Holocene tectonic activity is unlikely to have triggered landslides in the study area.

Surficial geology has been reported in maps and reports prepared by the Alberta Research Council and by the Geological Survey of Canada (Gravenor and Bayrock, 1955; Gravenor, 1956; Bayrock, 1958; Shetsen, 1987). These document the type, distribution and mode of origin of the surficial materials. The thickness of surficial deposits on the Alberta Plains is also included in the Alberta Geological

Survey's Bedrock Topography Series Maps. Ground moraine, ablation moraine and hummocky disintegration moraine deposited on the bedrock surface have been identified. Glacio-lacustrine sediments are also widely distributed throughout the Alberta Plains.

Hydrogeological information on the study area is provided by Meyboom (1960), Farvolden(1963), Chase (1969) and Tokarsky (1986). Heterogeneity in the regional geology may have produced complex regional groundwater regimes. However, the flat-lying geological units, as well as the surficial deposits, are regarded as essentially the same on both N- and Sfc slopes in a given valley. Gently dipping geological units in some areas control the groundwater flow direction (Borneuf, 1972), which could have affected landslide incidence. Since dip direction is southwest, if groundwater flow has any effect on landslide incidence on N- and Sfc slopes, it is most likely to increase the incidence on the Sfc slopes. Significantly higher landslide incidence on the Nfc slopes along Red Deer and Bow Rivers (Chapter 2) indicates that dip direction is not an important controlling factor.

1.5.3 Climate and Vegetation

Phillips (1990) and Hare and Thomas (1979) systematically classified the climate of Alberta according to different parameters, such as temperature and precipitation. These are in turn controlled mainly by air mass types, topography and variable maritime influences (Phillips, 1990, p.120).

Numerous climate classifications have been applied to the province of the Alberta from earlier schemes (Koppen, 1931; Thornthwaite, 1933; Trewartha, 1954) and later revised classifications (Papadakis, 1970; Hare and Thomas, 1979; Strong and Leggat, 1981; Ecoregions Working Group, 1989; Phillips, 1990). Longley (1972, pp.70-72) applied a revised Koppen classification to the Prairie Provinces of Canada and detailed the climatic classification in Alberta except for mountainous regions. All classifications are based on basic climatic factors, such as temperature, precipitation and its seasonal distribution, evaporation (or evapotranspiration), as well as the combination of the characteristics of vegetation. However, the most recent ecoregions classification (Strong and Leggat, 1992) has become the "provincial standard for the classification and identification of Alberta's regional climate and vegetation. It has received widespread use by various government agencies, educational and research institutions" (Strong and Leggat, p.1, 1992). Based on over ten years of observations at 211 weather stations, and using monthly climatic data and derived parameters, Strong and Leggat (1992) divided Alberta into three major climatic regions, or ecoprovinces: Grassland, Cordilleran and Boreal. These regions generally correspond to other classifications previously described. Within the three climatic regions occur 13 distinctive climatic subregions as represented by vegetation and associated physical attributes.

According to Strong and Leggat's (1992) classification, the study area lies within the Grassland Ecoprovince, which is further divided into Dry Mixed Grass, Mixed Grass, Fescue Grass and Aspen Parkland. The study area covers all except the Fescue Grass. The grassland ecoprovince has a continental climate with cold winters, short summers, and low precipitation. The primary controlling factors are latitudinal position and air mass types.

The Battle River area lies within the Aspen Parkland with average annual precipitation of 412mm and mean annual temperature of 3.3 °C, and the dominant climatic regime is Prairie-Boreal (Strong and Leggat, 1992). The Aspen Parkland is a transition zone between true forest and grassland environments. It is bounded on the north by boreal forests and on the south by grasslands. The Aspen Parkland is defined as a mixture of native grassland and deciduous forest plant communities in the form of parkland.

The Red Deer River area lies mostly within the Mixed Grass ecoregion, but the east portion is in the Dry Mixed Grass ecoregion. The Bow River area is totally within the Dry Mixed Grass ecoregion. The Mixed Grass ecoregion, located west and north of the Dry Mixed Grass Ecoregion, is drier than the Aspen Parkland. The annual precipitation in this region is 326mm and the mean annual temperature is 5.3 °C, while the Dry Mixed Grass has even less average yearly precipitation (272mm) but similar temperature (5.0 °C) (Strong and Leggat, 1992). The dominant climatic regime for both regions is Prairie.

In terms of summer precipitation, the Aspen Parkland has higher rainfall (259mm) than the other two (176mm for Mixed Grass and 156mm for Dry Mixed

Grass). But winter snowfalls in the three regions are similar to each other with the values of 53, 52, and 48mm of water equivalent for Aspen Parkland, Mixed Grass and Dry Mixed Grass regions respectively. It is clear that it is the summer precipitation which differs most among the three ecoregions, and the summer precipitation could be a major controlling factor because almost all historic recorded landslides happened during the summer months (Cruden, 1996).

The predominant plant species are described in detail in Strong and Leggat (1992). However, the distribution of plants on the valley walls of the three rivers differ from the average species in the ecoregion because of slope aspect effects. Nfc slopes usually have much taller and denser plant cover than the Sfc slopes, a difference equivalent to that found across several degrees of latitude in flat-lying regions. The details of these differences are covered in Chapter 4.

1.5.4 Postglacial history of the three river valleys

The study area was free of ice by about 12,000 B.P (Stalker, 1973; Dyke, and Prest, 1987; Shetsen, 1990; Hickman, and Schweger, 1993), but a recent study by Campbell and Campbell (1997) indicates that deglaciation was probably complete prior to 15,000 cal ^{14}C yr. B.P, based on ^{14}C dated material from proglacial lakes. The three studied sections of the Battle River, Red Deer River and Bow River valleys are believed to be postglacial meltwater channels (Stalker, 1960, 1965), though portions or all of the three sections possibly originated subglacially (I. A. Campbell, R. B. Rains, pers. comm, 1998).

Previous studies have given no conclusive evidence to show that the modern Red Deer River valley is in a preglacial channel. Various publications that claimed that the section on the Red Deer River in the study area follows a preglacial valley were often based on the same original sources, such as the bedrock topography, and hydrogeology maps (Stalker, 1960; Carlson, 1970, 1972; Carlson, et al.,1969; Tokarsky, 1988; Pawlowicz, and Fenton, 1995). Digitized provincial preglacial valleys based on bedrock topographical maps show that the Red Deer valley could be a tributary of the preglacial Red Deer valley (R. Young, per. comm., 1998), though there is no conclusive evidence so far to verify this observation.

Detailed mapping of the section revealed no evidence from the valley crest that it is a preglacial valley since the exposure of bedrock on both river sides is extensive. To refer back to some previous studies, especially the map of the hydrogeology of the Drumheller area (Borneuf, 1972), sand and gravel deposits extend from East Coulee down to the south across the Red Deer River in the study area. The cross-section in Borneuf's (1972) map clearly shows the deposits of gravel and sands. It is not clear if this indicates a preglacial valley or an early postglacial valley since it is not known if till overlies the gravel and sands. Carlson et al's (1969) bedrock topography map also shows a possible preglacial valley from East Coulee down to the south across the Red Deer River, and this is consistent with the sand and gravel deposits reported on maps of Borneuf (1972) and Carlson et al. (1969). All of this indicates that the preglacial valley may have crossed Red Deer valley from East Coulee to the south, and the river section mapped is not in a preglacial valley. According to Scott and Brooker (1968), downcutting of the Red Deer River in the study area mainly occurred during post-glacial time. Changes in base level during development of the valley are evidenced by the presence of well defined terrace levels.

It can be inferred that the section of the Red Deer River is not in a preglacial valley. A possible valley which turned south from East Coulee across the Red Deer River to the south as shown by the gravel and sands deposits could be either an early postglacial valley or a preglacial valley. However, there is not any evidence so far that the mapped section of the Red Deer River in the study area is in a preglacial valley. There is a possibility that there may have been a small and shallow tributary of the preglacial valley, but, as the modern river would have completely eroded the preglacial deposits away, they would have no influence on slope stability.

Postglacial valleys in the study area in southern Alberta possibly started developing at the margin of the Laurentide ice sheet during the ice sheet retreat. The Battle and the Red Deer rivers possibly started developing subglacially during ice retreat (Paterson, 1996; R. B. Rains, 1998, pers. comm.). This may explain why the present Battle River is such an under-fit channel (Bayrock, 1958; Stalker, 1960). The downcutting of the river probably valleys started immediately after the ice retreat. A study in part of the North Saskachewan River valley indicates that fast downcutting was completed around 8000 B.P.(Rains and Welch, 1988). The age of the terraces in the Ghostpine tributary of the Red Deer River shows that over half the valley depth was eroded between approximately 13,000 and 7,600 B.P. (Rains, et al., 1994), and slow downcutting is continuing to present. It is likely that much of the downcutting of the valleys was largely completed well before 8000 BP. For landslides where the whole valley wall was involved, the approximate ages of the landslides may be younger than 8000 BP. The age of the oldest landslides dated by Goulden and Sauchyn (1986) in Cypress Hills is 7259±165 yrs. B.P., which shows a coincidence with the results of Rains and Welch (1988) and Rains et al.(1994). Their consistent results suggest approximate synchronisation of events. Climatic conditions around 8000 B.P. were drier than present, and gradually became moister and colder after that (Campbell and Campbell, 1997).

1.6 Outline of the Thesis

Chapter 1 has presented a general introduction to the topics covered in this thesis. Chapter 2 focuses on the landslide incidence on the Battle River, Red Deer River and the Bow River. Chapter 3 models the direct short-wave radiation, evapotranspiration and Agro-Meteological Index on sloping surfaces on the banks of the three river valleys. Chapter 4 focuses on the vegetation characteristics on the N- and Sfc slopes, as well as slope angles along the different river valleys and on N- and Sfc slopes.

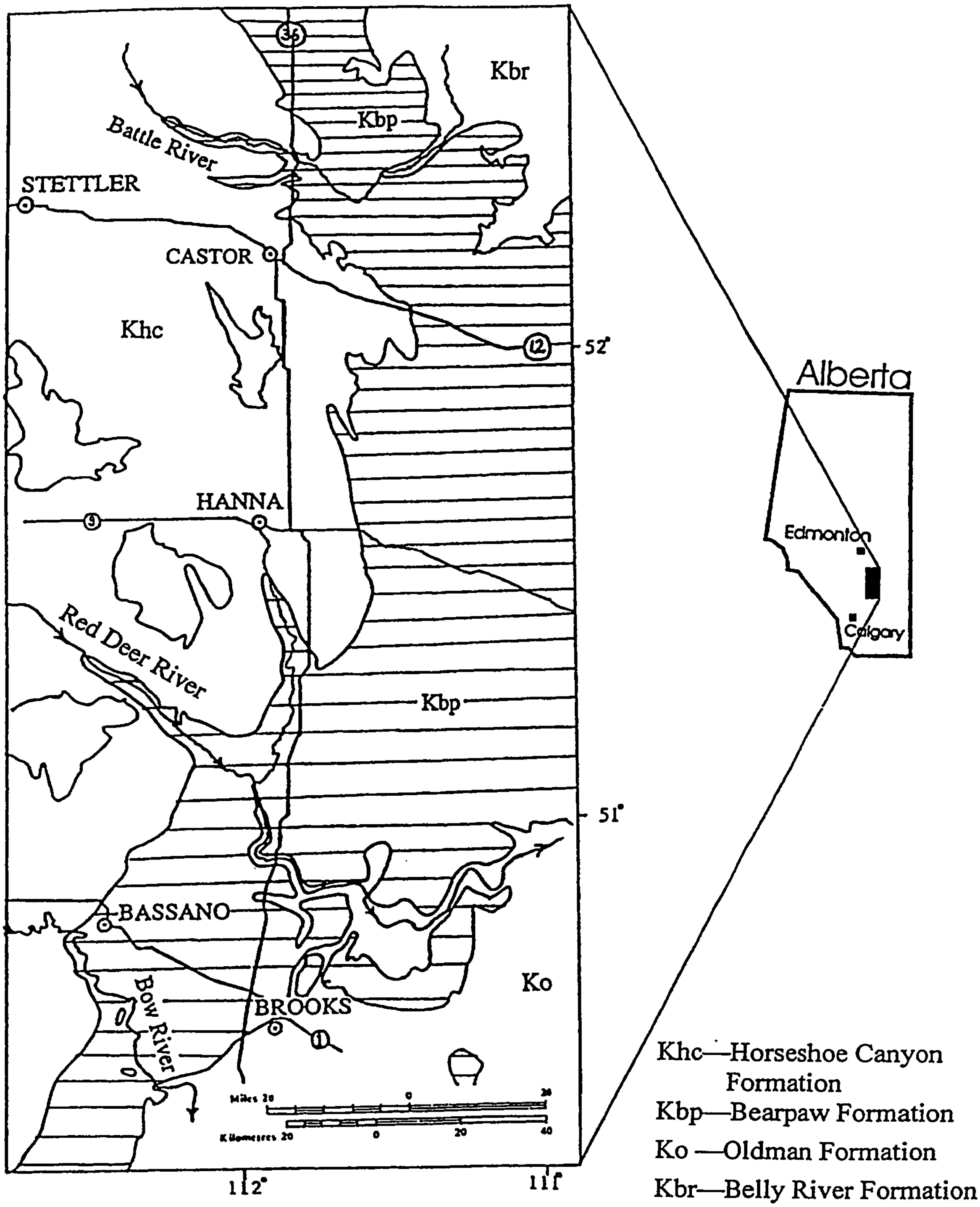


Figure 1.1 Location of study area.

Chapter 2

Landslide Incidence on the Slopes of Three Rivers in the Bearpaw Formation, Southern Alberta

2.1 Introduction

Interest in landslide activity has been focused along the major rivers in Alberta. Landslide incidence, or the distribution of landslides on river sides in southern Alberta, has been studied by Arvidson (1972); Thomson and Morgenstern (1977); Thomson and Bruce (1978) and Cruden et al. (1991). The general conclusions from these studies were that landslide incidence increased towards the northern part of southern Alberta, and correlates closely with bedrock types. One cause of the higher incidence in the northern part of southern Alberta was cited to be climate (Beaty, 1972a, 1972b; Arvidson, 1972; Cruden, et al., 1989; Cruden, et al., 1991). However, Thomson and Morgenstern (1977) suggested that the effects of microclimate were only minor compared to other factors. Arvidson (1972) concluded that failed slopes dominantly faced north. A similar conclusion arose from Beaty's study (1972b); in southern Alberta, where a remarkably higher proportion (75%) of slope failures had occurred on slopes of northerly, northeasterly, and easterly aspects than on slopes of other aspects. Greater natural moisture accumulation due to lesser insolation on these exposures appears to have been the primary controlling factor (Churchill, 1981; Radke, 1982). Reid (1973) showed the slope orientation affected annual soil moisture, and was significant in altering the gross hydrological balance over an extended period of time.

Chapter 2 focuses on the mapping of landslide incidence in the three sections in the three rivers. Detailed maps of landslide incidence in the three sections on the three rivers are presented on airphoto overlays in Appendices A, B and C based on the mapping procedures outlined in section 2.1.1. The calculations of landslide incidences according to the mapping procedures are documented in section 2.1.2. Sections 2.3.3.1 and 2.4.3.1 provide detailed statistical analyses of the differences in landslide incidences between N- and Sfc slopes and other slope orientations. Sections 2.3.3.3 and 2.4.3.3 examine pairwise statistical analyses of the relationships between every pair of landslide incidences in different sectors of slope aspects along the Red Deer and Bow Rivers.

2.1.1 Landslide mapping procedures

Air photo interpretation was used to map landslides in the study area. Air photographs provide a three-dimensional model of the soil, vegetation, geology and natural features of the study area. Characteristics of each landslide such as size, shape, activity and type are also captured by the air photos. Field investigation and verification of the air photo overlays on N- and Sfc slopes on the three river sections in the study area used air photos at a scale of 1: 31,680 (one inch equals

2640 feet) for the Red Deer and Bow Rivers and 1: 30,000 for the Battle River. The airphotos dating from 1968, 1978 and 1984 used for the mapping are not the most recent. However, a few slides which were not shown on the photos needed to be added to the overlays.

Existing maps of bedrock geology (Geiger, 1967; Carlson, 1969, 1970, 1972; Pawlowicz and Fenton, 1995), surficial geology (Geological Survey of Canada, 1960; Bayrock, 1967), geology (Allan and Sanderson, 1925; Allan, and Sanderson, 1946; Rutherford, 1939; Warren and Hume, 1939; Irish, 1971; Robert, 1972; Yoon, 1974; Jerzykiewicz, 1997) and Quaternary geology (Bayrock, 1958; Shetsen, 1987) assisted the mapping in each of the three river sections.

Air photo interpretation gave an overview of slope instability along the river valleys and field identification and the interpretation were carried out to accomplish the final landslide mapping. The criteria for the identification of landslides are that valley geometry, stratigraphy, and geomorphology clearly indicate that landslides have occurred. These criteria are comparable to those needed in work carried out in the previous studies, but they do not distinguish between active and inactive slides. Generally, about 80% of landslides are relatively old (Arvidson, 1972). The reason for mapping inactive landslides is that they demonstrate that the slope is unstable at an angle only slightly steeper than the present slope. Unstable slopes often contribute to reactivation of old landslides (Radbruch-Hall, et al., 1982).

2.1.2 Modes of landslides

The types of landslides in the study area are mainly thick rotational or compound slides. This is consistent with the findings of other studies (Thomson and Morgenstern, 1977, 1979; Bolduc, et al., 1988). Sometimes, flow slides were found on old landslides (Arvidson, 1972). This type occurs particularly in the Bearpaw Formation. The term compound slides (Varnes, 1978) refers to movements having a partly rotational and partly translational character. Rotational slides have cylindrical surfaces of rupture that are generally concave-up. The surfaces of rupture of compound slides are formed of combinations of curved and planar surfaces, and are spoon-shaped and concentric in plan view (Bolduc, et al., 1988). Previous studies and field mapping indicate compound slides are the most common type of landslide in the Bearpaw Formation in southern Alberta.

Generally, the landslides mapped have relatively steep scarps with back-tilting of the heads of the displaced materials. This is especially the case in the western portion of the Bearpaw Formation along the Battle River due to the presence of a strong sandstone caprock in the western section of the Battle River.

Detailed site-specific studies (Cruden et al., 1995) along the Battle River indicate that the material involved in the landsliding is softened, deeply weathered, and poorly indurated, bedrock or colluvial material. If it is colluvial material, it is mostly the reactivation of old landslide deposits, and if it is softened bedrock, it has no cohesion (Cruden, et al., 1995) due to weathering effects. Because of these physical properties of the material, it is more climatically sensitive than the unweathered bedrock.

2.1.3 Calculation of landslide incidence

Landslide incidence on the three river sections in the Bearpaw Formation was assessed by the following approach. In general, the mapping of the three river sections started from where the top of the Bearpaw dips westerly below the toe of the valley slope, and ended in the east where the base of the Bearpaw intersects the crest of that valley. First, two-kilometre reaches along main river channels on airphoto overlays were drawn; then, two lines on valley crests (left and right sides) parallel to the two-kilometre unit lengths following the river channel were drawn along the entire section of the Bearpaw Formation on each river (Figure 2.1).

Local irregularities in the valley crests were eliminated by approximating the crests as straight lines for relatively straight river sections. If the two lines involved are in river meanders, the length of the line on the crest on inner meander is shorter than 2 km (BB'<2 km) (Figure 2.1), and that on the outside of the meander is longer than 2 km (AA'>2 km). This does not increase or decrease the landslide incidences on the inside or the outside of the river meanders since the landslides that occurred around river meanders intersecting a crest line can be projected on to the measurement line AA' (ab is projected to aB' in Figure 2.1) to represent the length of valley crests involved in landsliding (Figure 2.1). Tributary effect is eliminated by excluding the length of the crest line from the measurement where the tributary cuts the river crest. By doing this, the portions of each pair of measurement lines parallel to the unit 2 km length along the main river channel more accurately represent the percentage of the valley wall involved in landsliding. Following this procedure, the percentage of slope failure is calculated by dividing the aggregate landslide distance in the interval by the unit length along the main river channel. Following the same approach, landslide incidences are calculated on both sides along each of the three rivers in the Bearpaw Formation. The detailed mapped sections on the three rivers are listed in Appendices A, B and C. The landslide incidence on each river is discussed in detail in the following sections.

2.2 Landslide incidence along the Battle River

2.2.1 Physical features of the mapped section of the Battle River

The Battle River is an under-fit river in a glacial meltwater channel (Bayrock, 1958; Stalker, 1960). The valley wall slope toes are untouched by the Battle River except at one measurement point (see Appendix A). Relict landslides (Cruden and Varnes, 1996, Ch. 3), probably triggered by glacial meltwater undercutting, are still recognisable by the presence of their displaced masses. Successive landslides are well developed in the section where no caprock exists (A4, A5 and A6 in Appendix A). Successive landslides are characterized by a step-like pattern on the valley wall that can be explained by Hutchinson's (1973) slope model (Chapter 4), especially in the eastern half of the portion studied (A4, A5 and A6 in App. A). The linear arrangement of trees across N- and Sfc slopes established on the minor backscarps (risers of the steps) of the successive landslides is an excellent indication of the step-like pattern as shown in Appendix A.

The slopes of valley walls along the Battle River average 6.4°, excluding the crests of the valley wall and the scarps of landslides. The slope length of valley wall varies from 300 m to 1000 m for the mapped section, and increases from the west to east. The width of the valley from crest to crest across the valley varies from 1 km to 3 km from the start to near the end of the mapped section of the Battle River. The width of the valley is greatest where the sandstone caprock layer ends (see photos 9 and 10 in Table 2.1 and Appendix

A). It is clear that the stratigraphically controlled width of the valley is greatest where no caprock exits. Otherwise, the valley is narrower, and the slope has a bilinear profile composed of a steeper upper slope on which landsliding is initiated (the degradation zone) and a flatter lower slope (the accumulation zone) of colluvium (Hutchinson, 1973). The difference in widths is about 1 to 2 km in magnitude. The valley floor is level and has a uniform width of about 500 m across the valley in the mapped section. Surficial deposits at prairie level near the river valley consist mainly of till and lake deposits (Bayrock, 1958, 1960; Stalker, 1960).

Table 2.1 Airphoto numbers on the photo coverage map on the Battle River

Photo scale, 1: 30,000 year: 1984

No. on Figure 2.2	Roll Number	Line Number	Print Number
1, 2, 3	AS 3026	LN. 9	251, 252, 253
4, 5, 6, 7	AS 3026	LN. 10	280, 281, 284, 285
8, 9, 10	AS 3027	LN. 11	021, 022, 023,024

2.2.2 Landslide incidence in the mapped section

The section of the Battle River along which the Bearpaw Formation occurs is shown on Figures 1.1, 2.2, and the airphoto coverage is listed in Table 2.1. The total length of the Bearpaw Formation exposed in the Battle River valley from slope toes to crests is approximately 45km, and the section mapped is about 24km in the eastern half, as shown on the coverage Figure 2.2. Airphotos used for the study of this section are 1: 30,000 scale photos taken in 1984.

Because the western half of the valley wall of the 45 km stretch of the Battle River was severely dissected by numerous tributary melt-water channels, this half was not mapped. The mapped eastern half is 24 km (2 km per measurement). Landslide incidence incidence along the mapped section is almost 100% on both N- and Sfc slopes in most of the 2 km segments (Table 2.2), except in two segments on each of the N- and Sfc slopes. The average landslide incidence on the Nfc slope is slightly higher than the Sfc slope. However, the difference is not statistically significant. Because the incidences on both valley sides are almost 100%, individual landslides cannot be clearly separated on N- and Sfc slopes. Only the non-landslide sections along the valley on both sides are marked off to distinguish them from landslide sections (Appendix A).

Table 2.2 indicates that landslide incidences on both N- and Sfc slopes are above 95% along the Battle River in the mapped section. Field investigations and airphoto studies reveal that most of the slides are very old, excepting about 35 small landslides whose lengths are from 10 to 20 m, and a 600 m long landslide where the whole slope is involved (Distance 12 to 14) (Appendix A). These occur near river meanders because of toe erosion.

2.3 Landslide incidence along the Red Deer River

2.3.1 Physical features of the mapped section of the Red Deer River

The 58 km section mapped along the Red Deer River in the Bearpaw Formation is from Hoodoo (to the west of East Coulee), where the top of the Bearpaw intersects the bottom of the valley of the Red Deer River, to the section where the base of the Bearpaw intersects the top of the valley wall of the river (see Appendix B and Figure 1.1). Airphotos taken in 1968 and 1974 at a scale of 1:31,680 were used. The photo coverage is shown on Figure 2.3, and the photos numbered on the cover map (Figure 2.3) are listed in Table 2.3.

Table 2.2 Measurements of landslide incidence on the Battle River.

Photo scale, 1: 31, 680 year: 1974

	Nfc slope			Sfc slope		
Distance	Crest_len	Slide_len	Incidence(%)	Crest_len	Slide_len	Incidence(%)
2	6.6	6.6	100	6.6	6.6	100
4	7.3	7.3	100	6.1	6.1	100
6	6.6	6.6	100	6.5	6.5	100
8	6.7	6.7	100	6.6	6.6	100
10	7.3	6.3	86.3	5.8	4.3	74.1
12	7.8	6.3	80.8	4.8	3.3	68.8
14	6.8	6.8	100	6.4	6.4	100.0
16	6.7	6.7	100.0	6.6	6.6	100.0
18	5.3	5.3	100.0	8.1	8.1	100.0
20	5.5	5.5	100.0	8	8	100.0
22	6.9	6.9	100.0	6.3	6.3	100.0
24	6.6	6.6	100.0	6.6	6.6	100.0
			97.26			95.24

Crest_len and *Slide_len* refer to the length of the crest and the horizontal distance of the slope involved in landsliding per measurement made on airphotos. The unit length is 2km.

Table 2.3 Airphoto numbers on the photo coverage map on the Red Deer River. *Crest_len* and *Slide_len* have the same definition as in Table 2.2.

scale, 1: 31, 680 year: 1974

No. on Figure 2.3	Roll Number	Line Number	Print Number
1, 2	AS 1332	LN. 9	288, 289
3, 4, 5	AS 1333	LN. 10	1, 2, 3
6, 7, 8	AS 1333	LN. 11	49, 50, 51
9, 10	AS 1333	LN. 12	111, 112
11, 12, 13	AS 1333	LN. 13	158, 159, 160
14, 15, 16	AS 1333	LN. 14	212, 213, 214
17, 18, 19	AS 1333	LN. 15	264, 265, 266
20, 21, 22	AS 1334	LN. 16	2, 3, 4
23, 24, 25, 26	AS 1334	LN. 17	59, 60, 61, 62, 63
27, 28, 29	AS 1334	LN. 18	121, 122, 123

The reach mapped along the Red Deer River is straight with an average width from crest to crest of 2.3 km and a valley wall height of about 76 m. Slope angles average 11.3°, steeper than those along the Battle River. This section of the Red Deer River may be entrenched in the preglacial Red Deer River valley (Broscoe and Barton, 1959; Pawlowicz and Fenton, 1995). Stalker (1961) showed that the Red Deer River follows its preglacial valley downstream to Red Deer, from where the preglacial valley turns eastward. Studies based on the bedrock topography maps and hydrogeology maps show that the section along the Red Deer River in the study area may be a tributary of the preglacial Red Deer valley (Farvolden, 1963; Tokarsky, 1988, Young, 1998, per. comm). There are exposures of preglacial fluvial deposits downstream of the section of the Red Deer River valley in Dinosaur Provincial Park (Farvolden, 1963; Tokarsky, 1986; Evans and Campbell, 1995; Pawlowicz and Fenton, 1995), where the modern Red Deer River may flow in the preglacial Bow River valley. The section of the modern Red Deer River valley between Drumheller and Dinosaur Provincial Park shows, however, no evidence that it is in a preglacial valley. Field work for this study showed that extensive exposures of the Horseshoe Canyon, Bearpaw and Belly River Formations on the slopes of the Red Deer River in the section exist, and no preglacial deposits were found on the slopes of the Red Deer River. If the modern Red Deer River valley is flowing in a tributary of the preglacial Red Deer valley, the preglacial valley would be very small, and presumably, postglacial river downcutting has completely removed all the deposits and widened the valley to its current state. However, glacial meltwater input to the Red Deer River prior to ca. 13,000 cal yr. B.P. (Campbell and Campbell, 1997) may have happened. The evidence at this point that the section of the Red Deer River occupies its preglacial valley is very generalised and based upon interpolations between townships with anywhere between 0 and 300 boreholes each (Carlson, 1970; Tokarsky, 1986).

The width of the valley from crest to crest and the length of the valley slopes gradually increase from Hoodoo (near Drumheller) to the end of the Bearpaw Formation. The width and length are 1.1 km and 450 m individually near Hoodoo and 3.0 km and 1.3 km near the east end of the 58 km reach, where the valley is the widest. The increasing width and the height are associated with the fact that the stratigraphy controls them. At Hoodoo, the beginning of the measurements of landslide incidence, the valley bottom is intersected by the top of the Bearpaw Formation. The valley wall is steep and short because the main portion of the valley wall is composed of relatively hard materials, sandstones and siltstones in the Cretaceous Horseshoe Canyon Formation (Khc) (see Appendix B). Following the thinning of the latter, valley width and length increase, and reach maxima where the whole valley wall is composed of the Bearpaw shale (B4, Appendix B). However, near the end of the measured section, Cretaceous sandstone Belly River Formation (Kbr) starts to intersect the base of the valley wall; consequently, the valley width and length decrease again (see Appendix B).

The valley wall of the Red Deer River is well exposed on both N- and Sfc slopes. There are two terraces on the Nfc slope (AS 1334 62, AS 1334 3, Appendix B) in the segment from 10 to 20 km, but none on the Sfc slope. The uplands are mantled by till and glacio-lacustrine deposits, but not on the valley walls, where the Bearpaw Formation has extensive exposure.

2.3.2 Landslide incidence along the mapped section of the Red Deer River

Landslide incidence reaches an average of 68% in the mapped section of this valley. Most slides are very old, but some are still active. For example, from distance 48-58 km, a CN railway track built on the top section of the valley wall on glacial deposits has been abandoned. Field investigation revealed active landsliding and deformation the Bearpaw shale beneath glacial deposits. Damage by landsliding and deformation of the shales led to its abandonment.

The types of landslides are similar to those found along the Battle River (mapped landslides in this section are listed in Appendix B). While the average landslide incidence is 68% (Table 2.4), there is a statistically significant difference

Table 2.4 Landslide incidence on N- and Sfc slopes of the Red Deer River

Scale: 1: 31, 680 Year: 1997

	Nfc Slope				Sfc Slope			
Distance (km)	Crest_len (cm)	Slide_len (cm)	Incidence (%)	Aspect (°)	Crest_len (cm)	Slide_len (cm)	Incidence (%)	Aspect (°)
2	6.4	5.6	87.5	60	6.2	1.2	19.4	240
4	6.4	6.1	95.3	56	5.9	1.4	23.7	236
6	6.7	6	93.8	32	5.9	3.2	54.2	212
8	5.7	4.7	82.5	26	6.3	2.6	41.3	206
10	6.3	4.8	76.2	33	6.3	5.9	93.7	213
12	5.7	5.7	100	21	6.1	5.6	91.8	201
14	6.1	4.6	75.4	18	6.5	3.4	52.3	198
16	5.7	4.5	78.9	36	6.7	1.9	28.4	216
18	6.1	3	49.2	39	6.7	2.2	32.8	219
20	6.4	5.4	84.4	48	6.3	1.9	30.2	228
22	6.4	5.4	84.4	41	6.2	3.6	58.1	221
24	6.1	5.9	96.7	43	6.4	3.4	53.1	223
26	6.4	6.4	100	48	6.3	2.3	36.5	228
28	6.7	6	89.6	41	6.1	4.1	67.2	221
30	6.5	6.3	96.9	45	6.3	4.5	71.4	225
32	6.4	6.2	96.9	40	5.7	4.2	73.7	220
34	6.3	4.9	77.8	37	6.4	1.1	17.2	217
36	6.2	4.1	66.1	39	6.5	1.9	29.2	219
38	5.7	3.9	68.4	45	6.9	1.3	18.8	225
40	6.7	5.3	79.1	52	6	1.6	26.7	232
42	6.8	6.8	100	28	5.8	4.1	70.7	208
44	6.3	5.9	93.7	19	6.3	5.7	90.5	199
46	6.3	3	47.6	31	7	1	14.3	211
48	5.9	5.1	86.4	53	6	1.8	30	233
50	6	1.3	21.7	63	6.5	1	15.4	243
52	6.2	6.2	100	68	6.4	6.1	95.3	248
54	6.3	6.3	100	76	6.3	6.3	100	256
56	6.3	6.3	100	67	6.2	6.2	100	247
58	6.3	6	95.2	65	6.3	5.9	93.7	245
Average			83.6	43.8			52.7	223.8

of landslide incidence between N- and Sfc slopes (Table 2.5). The incidence in the section on the Nfc slope is 84%, but on the Sfc slope is only 53% (Table 2.4). The plot of distance against landslide incidence in Figure 2.4 indicates a consistently changing pattern of incidence on N- and Sfc slopes, where the higher incidence on Nfc slope is coincident with the higher incidence on the Sfc slope. This pattern of landslide incidence may be caused by lateral variation of weak layers, perhaps bentonite in the Bearpaw Formation, where the thicker bentonites layers have higher landslide incidence on both N- and Sfc slopes, and where thinner bentonites have lower incidence.

Another possible cause for landslide localization may be regional joints Higher density of joints could yield higher landslide incidence. Because the direction of the river channels in southern Alberta may be controlled by regional joints, and the joints have an orthogonal relationship (Ozoray, 1972; Babcock, 1973), a landsliding direction perpendicular to the river channel has the same direction as the strike of the other joint set. This could be the cause of variations of landslide incidence along the Red Deer River and the Bow River (Figures 2.4 and 2.8). A rose diagram of the percentage of the frequency of landslide aspects on the Red Deer River (Figure 2.5) shows that the average aspects of the frequency is within the range of the strikes of regional joints studied by Ozoray (1972) and Babcock (1973) in southern Alberta. The directions of the strikes range from 30-55° and 120-145° (Babcock, 1973), and they have mutually perpendicular

Table 2.5 Statistical test of the difference of the observations of landslide incidence on N- and Sfc slopes.

ANOVA: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
LI on Nfc Slope	29	2423.7	83.576	347.3
LI on Sfc Slope	29	1529.6	52.745	886.41

ANOVA

Source of Variation	SS	df	MS	F	P-value	F- crit
Between Groups	13783	1	13783	22.344	$2x10^{-5}$	4.01
Within Groups	34543.9	56	616.86			
Total	48326.9	57				

--*N- and Sfc* , N- and Sfc slopes, individually;

--LI, landslide incidence.

directions which are either parallel to or orthogonal to the rock mountains (Ozoray, 1972). The diagram gives a reasonable indication of the possibility of the effect of joints on the variation of landslide incidence on the Red Deer River.

River meanders may have a strong influence but not play an important role in forming the changing pattern of landslide incidence at a small scale of 2 km unit length. Figure 2.4 shows that the higher landslide incidence on one side corresponds to the relatively higher incidence on the opposite side of the river in the study area. If river meanders control the pattern, the variation of the incidence on N- and Sfc slopes should have an opposite trend because the slope toe of the inside of the river meander is usually protected by fluvial deposits and the outside of the river meander is constantly eroded by the river.

Arvidson's (1972) study of landslide incidence on a regional scale indicates that that there is not a significantly higher landslide incidence along river meanders. The effect of river meanders may have been masked in this study by the approach used in the measurement of landslide incidence because the unit distance of measurement following the main river channel is 2 km which is longer than the average length of river meanders along the Red Deer and Bow Rivers. Even if the small section around the meander is prone to landsliding, the measurement including the section of the meander does not have to have higher incidence, as Figures 2.4 and 2.8 show. However, a lot of landslides are not caused by river erosion on N- and Sfc slopes (Appendix A, B and C). The higher landslide incidence on the Nfc slopes in tributary valleys of the Red Deer River in southern Alberta (Beaty, 1972b) and in South Dakota (Churchill, 1981) are good examples, where the landslides have little to do with river erosion. As a consequence, the measurements around river meanders do not show a higher landslide incidence based on the approach adopted in this study, which gives a good representation of slope stability on a regional scale, but not of the stability of a particular site.

Basic analyses have been carried out on the relationship between the slope aspect and landslide incidence on N- and Sfc slopes. Figure 2.6, plotting landslide incidence against slope aspects, shows that the incidence on NNE and ENE-facing slopes is much higher than on its opposite aspects. The overall scatter plot of the incidence against slope aspect (Figure 2.7) clearly indicates that the most measurements on Nfc slope have much higher incidence than on Sfc slope where the observations are clumped in a range of 20 to 40%. The distribution of the observations in Figure 2.7 gives a clear picture of the difference of the landslide incidence on differently facing slopes. The following section further covers the details of statistical analyses of landslide incidence on slopes with different aspects and statistical results.

2.3.3 Statistical analyses of landslide incidence and its relationship with slope aspect

Landslide incidences on N- and Sfc slopes are different (Table 2.4; Figures 2.1, 2.2 and 2.3). Two questions arise from this observation. First, are the observations of the landslide incidence on Nfc slopes significantly different from those on the Sfc slopes as appears in Figures 2.4 and 2.8? Second, are the means of the landslide incidences on N- and Sfc slopes statistically different? The following statistical tests focus on these questions.

The standard ANOVA (analysis of variance) for one single factor analysis is conducted based on the hypothesis that there is no difference between the mean landslide incidences on N- and Sfc slopes. Based on this hypothesis, and a significance level of $\alpha=0.05$, the single factor statistical results are listed in Table 2.5. The large F value shows that the null hypothesis should be rejected. The difference is significantly different at a confidence level of 95%. From a statistical point of view, there must therefore be a significant treatment to one or another group of the observations to cause the difference. In the study area, assuming that the geology on N- and Sfc slopes is the same, there must be other reasons to cause the difference of the landslide incidence.

2.3.4 ANOVA and Pairwise Test of Relationship between Landslide Incidence and Different Sectors of Slope Aspect

The single ANOVA (Table 2.5) has demonstrated the significant difference of the observations of landslide incidence as well as the means on N- and Sfc slopes. Multiple sample ANOVA is employed below to test if the observations of landslide incidences under different categories or sectors of slope aspects (0-45°, 45-90°, 90-135°, 135-270°, 270-315°, and 315-360°) are significantly different or not. By grouping the landslide incidences by categories of slope aspects, each group does not have the same number of observations, and this can be handled very well by this analysis. Slope aspect variable ASPECT is used as a grouping variable to identify the slope category. Landslide incidence (LI) is one column (the dependent variable) in this analysis (Table 2.6). The number of distinct data values appears as a category to determine how many sectors the full range of slope aspects can be divided into in the analysis. There are four sectors encountered in this analysis, representing four different aspects on the basis of a 45° interval designed for this dataset as well as for other datasets.

The hypothesis for this analysis is that there is no difference of landslide incidences in different slope aspects among the group. The results show that the difference of landslide incidence on different slope aspects is significantly different overall (Table 2.6), but this test cannot distinguish between which pair of the

Table 2.6 Statistical results of ANOVA on each sector of slope aspect at a difference of 45°.

SECTORS ENCOUNTERED DURING PROCESSING ARE:

ASPECT				
	45°	90°	225°	270°

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO*	P
ASPECT	13929.825	3	4643.275	7.289	0.000
ERROR	34397.094	54	636.983		

			LS MEAN	SE	N
ASPECT	=	45.000	81.9	5.949	18
ASPECT	=	90.000	86.3	7.610	11
ASPECT	=	225.000	53.3	5.949	18
ASPECT	=	270.000	51.9	7.610	11

--*SE*, standard error;

--*N*, numbers of observations in the aspect.

*--$F_{critical} = 2.18$.

sectors the difference of the landslide incidence is significant, even though the overall statistical results support the previous analyses. Table 2.6 shows the pairwise mean differences of landslide incidence at each sector, mean standard error (MSE), and the probabilities among different sectors.

The tests conducted so far have shown that landslide incidence is higher on Nfc slopes and lower on the opposite slopes, and also that the landslide incidences are significantly different among the different slope aspects at a 45° interval. The result raises the question, however, as to which pairs of the groups of the landslide incidence incidences are significantly different. The test, Tukey HSD pairwise multiple comparisons (Miller, 1985) looks into the details of this question.

The simultaneous pairwise multiple comparison test procedures are designed to test differences among every pair of datasets at different levels. These are used to test differences between each pair of landslide incidences at different sectors of slope aspects at 45°. The first tentative test is set up to test the differences of landslide incidences at their corresponding sectors of slope aspect at a consistent increase of 45° from up to 45° and above. By doing this, the slope aspects can be divided into eight sectors, 0-45, 45-90, 90-135, 135-270, 270-315, and 315-360 degrees. Then, the landslide incidences in each half quadrant of slope aspect are statistically compared. If the differences are significantly different, that means the incidence may be affected by slope aspect.

The test is conducted with SYSTAT/MGLH/HYPOTHESIS (Wilkinson, 1990, p.215-316) under the function of Analysis of Variance. The category of slope aspect is 45 degrees. The Tukey HSD multiple comparison matrix (Table 2.7) gives the probabilities of the differences at 0.05 level between each pair of the incidences based on the hypothesis that there is no difference between every pair of the landslide incidences at their sectors. The slope aspects are only within four of the eight sectors (45° per sector), and test results from the matrix of pairwise comparison probabilities show that the differences of landslide incidence between the pair of NNE (0-45^0) and ENE (45-90^0) aspects, as well as between the pair of SSW (180-225°) and WSW (225-270 °) aspects, are not statistically significant ($P>0.05$). However, the landslide incidence in either of the first pair is significantly different from the landslide incidence in either of the second pair of the aspects. This test further verifies the preference of higher landslide incidences for Nfc aspects, and that there is no significant difference of the incidences in the aspects of NNE and ENE, and in the aspects of SSW and WSW. These results are also consistent with the results of one single-factor ANOVA.

There is no statistical significance if the category, slope aspect, is divided further because of limited measurements within a subdivision of the category slope

Table 2.7 Pairwise multiple comparison analysis of the relationship between slope aspects and landslide incidences.

Statistical Analysis Table

COL/ ROW	ASPECT
1	45°
2	90°
3	225°
4	270°

USING LEAST SQUARES MEANS.

POST HOC TEST OF LANDSLIDE INCIDENCE

USING MODEL MSE OF 636.983 WITH 54. DF.

MATRIX OF PAIRWISE MEAN DIFFERENCES:

	1	2	3	4
1	0.000			
2	4.433	0.000		
3	-28.633	-33.066	0.000	
4	-29.994	-34.427	-1.361	0.000

TUKEY HSD MULTIPLE COMPARISONS.
MATRIX OF PAIRWISE COMPARISON PROBABILITIES:

	1	2	3	4
1	1.000			
2	0.968	1.000		
3	0.007	0.006	1.000	
4	0.016	0.012	0.999	1.000

aspect and less significance of the influence by slope aspect if the 45° is divided further.

2.4 Landslide incidence along the Bow River valley

2.4.1 Physical features of the mapped section of the Bow River valley

The mapped section along the Bow River valley (Appendix C) in the Bearpaw Formation is from south of Bassano Dam (distance 0 km) to west of Bow City (distance 44km). There are 44 paired measurements on N- and Sfc slopes: 22 on each slope. Each pair measurement is taken at 2 km interval along the main channel of the Bow River on N- and Sfc slopes. The top of the Bearpaw Formation starts to intersect the valley to the western side of the Bassano Dam (see Appendix C). At the end of the section the base of the Bearpaw intersects the top slopes of the valley. Airphotos used for this section of Bow River valley were taken in 1962 at a scale of 1: 31, 680. The photo coverage is shown on Figure 2.8. Index numbers of the photos are listed in Table 2.8. The stretch mapped along the Bow River is quite sinuous, reflecting control by the regional joint structures (Stalker, 1961; Babcock, 1973). The valley is relatively small in comparison with the other two rivers. Average width (at crest) is 1.3 km and the slope length of the valley walls lies in the range 51 m to 870 m. Variation in width is relatively uniform throughout the whole mapped section. The Horseshoe Canyon Formation above the Bearpaw

Table 2.8 Airphoto numbers on photo coverage map on the Bow River

year: 1962

No. on Figure 2.8	Roll Number	Line Number	Print Number
1, 2	YC 562	C 62.651-5010	50, 51
3, 4, 5	YC 539	C 62.651-5011	46, 47, 48
6, 7	YC 586	C 62.651-5012	15, 16
8, 9, 10	YC 570	C 62.651-5013	128, 129, 130
11, 12, 13, 14	YC 574	C 62.651-5014	14, 15, 16, 17
15, 16, 17	YC 574	C 62.651-5015	46, 47, 48
18, 19, 20	YC 597	C 62.651-5016	14, 15, 16
21, 22, 23	YC 574	C 62.651-5017	94, 95, 96

Formation extends only about 6 km downstream from the beginning of the measurement of landslide incidence. The top caprock portion of the Bearpaw is either very thin or absent, and the whole valley is mostly composed of pure shale, a material prone to landsliding. Bow River also has steeper valley walls than either Battle River or the Red Deer River with an average slope angle of 14.8°.

Stalker's (1961) study indicated that the modern Bow River follows a preglacial valley from the mountains eastward to Bassano; at Bassano the modern river leaves the preglacial valley to flow southward towards the Oldman River. Preglacial deposits were found by Chlachula (1996) in the upper Bow River valley around the city of Calgary. Pawlowicz and Fenton's map (1995) of the thalwegs of preglacial valleys shows that the section (from distance 0 to 44 km, see Appendix C) of the Bow River, southeast of Bassano, is not in its preglacial valley, and is in its postglacial valley. Postglacial erosion can be witnessed by deeply incised canyons, high-elevation postglacial terraces, extensive alluvial deposits, and the spillway outlets which cross the current valley and which can be found on the crest of the valley near the end of this section (C8, Appendix C). Glacial lake deposits of fine sands, silts and clays are found here, together with ground moraine deposits which vary in thickness up to 10 m (Arvidson, 1972).

2.4.2 Landslide incidence in the mapped section of the Bow River valley

Landslide incidence along the Bow valley is the lowest among the three rivers in the mapped section, although, the average is still around 30%. Most of landslide types do not differ significantly from the types found on the Battle and Bow Rivers, but dry flows may be more frequent in this section than along the Red Deer River. Even though average landslide incidence is not high, the difference between N- and Sfc slopes is still significant: average incidence is 46.6% on Nfc slope and 11.6% on Sfc slopes. Detailed maps of landslides in this section of the Bow River are listed in Appendix C. The mapped landslide incidences along the Bow River are listed in Table 2.9.

Table 2.9 gives a clear picture of the difference of the incidence in this section on N- and Sfc slopes. Figure 2.9, mapping distance against the landslide incidence, shows the continuous variation of the incidence following the river channel on N- and Sfc slopes. As in the section on the Red Deer River, the incidence clearly indicates a consistent changing pattern between N- and Sfc slopes slopes along most of the section. The same causes as suggested in Chapter 2.3.2 for the Red Deer River could be applied here as well, the presence of bentonite

Table 2.9 Landslide incidence on N- and Sfc slopes of the Bow River.

Year: 1997

	Nfc Slope				Sfc Slope			
Distance (km)	Crest_len (cm)	Slide_len (cm)	Incidence (%)	Aspect (°)	Crest_len (cm)	Slide_len (cm)	Incidence (%)	Aspect (°)
2	7.3	5.6	76.7	76	5.4	1.7	31.5	256
4	5.9	4.3	72.9	19	6.9	2.6	37.7	199
6	6.8	2.6	38.2	276	4.6	0.5	10.9	96
8	7.9	1.7	21.5	84	5.8	0.4	6.9	264
10	6.5	5.1	78.5	19	6.3	1.2	19	199
12	7.3	4.9	67.1	276	5.6	1.8	32.1	96
14	7.1	5.4	76.1	61	5.1	1	19.6	241
16	7.1	3.4	47.9	18	5.2	0	0	198
18	6.2	1.1	17.7	4	6.9	1.1	15.9	184
20	5.9	1.6	27.1	32	6.7	1	14.9	212
22	5	2.4	48	22	8.2	0.9	11	202
24	8.6	3.1	36	275	4.6	0	0	95
26	6	5.7	95	298	6.6	2	30.3	118
28	8.2	6.3	76.8	72	4.9	0	0	252
30	6	3.7	61.7	25	6.8	0.7	10.3	205
32	7.9	2.3	29.1	284	4.6	0	0	104
34	6	2.2	36.7	275	6.5	0.3	4.6	95
36	6.5	3.3	50.8	85	6	0.1	1.7	265
38	7.1	2.1	29.6	57	5.1	0	0	237
40	6.4	2.1	32.8	49	6.2	0	0	229
42	6.2	0	0	48	6.7	0	0	228
44	7.5	0.4	5.3	57	4.7	0.4	8.5	237
Total			46.6				11.6	191.5

deposits and regional joints. The rose diagram of the frequency of landsliding with aspect in Figure 2.10, shows two major preferred directions consistently within the range of strikes of joint sets in the region (Babcock, 1973).

Basic statistical methods have been applied to analyse the variation of the incidence on N- and Sfc slopes based on the measurements in Table 2.9. In order to analyse the relationship between the landslide incidence and its corresponding slope aspects, an eight-fold division of slope aspect is used here to reveal the relationship in Figure 2.11 which shows that the incidence on ENE, NNE and WNW-facing slopes is much higher than on their opposite aspects. The overall distribution of the measurements is represented in a scatter plot of the incidence against slope aspect (Figure 2.12). That figure shows that all the measurements on Sfc slope are below 40%, but almost half of the measurements on Nfc slope are in the range of 40-80%, and another half is less than 40%. Only two measurements on Sfc slope have higher incidence than their corresponding measurements on the opposite side of the valley wall. In the paired measurements, the Nfc slope is considered as from 0 to 90° and from 270 to 360°, and the rest is considered as Sfc slope.

Detailed statistical analyses are necessary to further reveal the relationship. The following section focuses on the details of statistical analyses of landslide incidence on differently facing slopes.

2.4.3 Statistical analysis of landslide incidence along the Bow River valley

Standard ANOVA (analysis of variance) is used to test if the paired measurements of landslide incidence on N- and Sfc slopes are significantly different as before. The hypothesis is that there is no difference between the observations of the landslide incidences on N- and Sfc slopes. The results of ANOVA single factor analysis are listed in Table 2.10 at a significance level of $\alpha=0.05$. The distinct F value ($F >> F_{criterion}$) as well as the very small value of P (0.0000001) generated by *MS EXCEL* rejects the hypothesis that the observations of the landslide incidences are the same on N- and Sfc slopes. The difference is significant, a scenario similar to the Red Deer River.

2.4.4 ANOVA and pairwise test of relationship between landslide incidence and different categories of slope aspect

The single ANOVA has proved the significant difference of the observations of landslide incidence as well as the means on N- and Sfc slopes.

Table 2.10 ANOVA single factor analysis of Landslide Incidence on the Bow River

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Nfc-slope	22	1025.5	46.6	676.145
Sfc-slope	22	254.9	11.6	148.4984

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	
Between Groups	13496.01	1	13496.01	32.73	9.99×10^{-7}	4.07
Within Groups	17317.51	42	412.32			
Total	30813.52	43				

These analyses are not enough, however, to reveal if the incidence in one specific sector of 45° range of slope aspect is significantly different from that in another sector of slope aspect. The slope aspects represented in Table 2.9 vary from 0 to 360°, and it is not wise to look into the incidence on N- and Sfc slopes by separating the observations along the 270°-90° axis in Figure 2.12. Based on this, a multiple sample ANOVA, similar to the analysis on the Red Deer River, is employed to test if the observations of landslide incidences in different slope aspects (0-45°, 45-90°, 90-135°, 135-270°, 270-315°, and 315-360°) are significantly different or not.

The same technique applied to the Red Deer River is used here by grouping the landslide incidences into individual sectors of slope aspect. The number of sectors as categories determines how many sectors of slope aspect are in this analysis. Six sectors, representing six different aspects, on the basis of 45° difference of slope aspect, are encountered in this dataset. The hypothesis is that no difference of landslide incidences on different sectors of slope aspects exists among all the sectors.

The results of the ANOVA of multiple samples listed in Table 2.11 show that the differences of landslide incidences on different sectors of slope aspects are significantly different overall (Table 2.11), but this test cannot distinguish in which

Table 2.11 Multiple sector analysis between slope aspect and the landslide incidence on the Bow River.

SECTORS ENCOUNTERED DURING PROCESSING ARE:
ASPECT

45	90	135	225	270	315

DEP VAR: LI N: 44 MULTIPLE R: 0.680 SQUARED MULTIPLE R: 0.462

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
ASPECT	14230.667	5	2846.133	**6.522**	**0.000**
ERROR	16582.853	38	436.391		

LEAST SQUARES MEANS

			LS MEAN	SE	N
ASPECT	=	45°	50.5	7.896	7
ASPECT	=	90°	41.1	6.963	9
ASPECT	=	135°	13.0	8.528	6
ASPECT	=	225°	15.5	7.896	7
ASPECT	=	270°	7.6	6.963	9
ASPECT	=	315°	50.4	8.528	6

pairs of the sectors the differences of the landslide incidences are significant. The overall statistical results however support the previous analyses as the Table 2.11 shows.

We have already concluded that the landslide incidence differs significantly under the influence of different sectors of slope aspects. But we still have no conclusion about whether the landslide incidence significantly differs between every pair of the sectors of slope aspects. The following pairwise multiple comparison offers simultaneous pairwise comparison of landslide incidence on every pair of slope aspects.

The sectors 1 to 6 in Table 2.12 refer to slope aspects in degrees as defined at the beginning of this analysis. The sectors of the individual numbers are as follows:

1	*0—45 ° (NNE)*	*2*	*45—90 ° (ENE)*
3	*90—135 ° (ESE)*	*4*	*180—225 ° (SSW)*
5	*225—270 ° (WSW)*	*6*	*270—360 ° (NNW)*

A matrix of pairwise comparison probabilities shows that the landslide incidences in NNE (0-45°), ENE (45-90°) and NNW (270-360°) aspects are not significantly different. The landslide incidences in ESE (90-135°), SSW (180-225°) and WSW (225-270°) aspects also show no significant differences. If the six aspects are

Table 2.12 Pairwise comparison of the relationship among different sectors of slope aspects and landslide incidences.

COL/ ROW	ASPECT
1	45°
2	90°
3	135°
4	225°
5	270°
6	315°

USING LEAST SQUARES MEANS.

POST HOC TEST OF LANDSLIDE INCIDENCE

USING MODEL MSE OF 436.391 WITH 38. DF.

MATRIX OF PAIRWISE MEAN DIFFERENCES:

	1	2	3	4	5	6
1	0.000					
2	-9.476	0.000				
3	-37.560	-28.083	0.000			
4	-35.000	-25.524	2.560	0.000		
5	-42.965	-33.489	-5.406	-7.965	0.000	
6	-0.193	9.283	37.367	34.807	42.772	0.000

TUKEY HSD MULTIPLE COMPARISONS.

MATRIX OF PAIRWISE COMPARISON PROBABILITIES:

	1	2	3	4	5	6
1	1.000					
2	0.944	1.000				
3	0.028	0.135	1.000			
4	0.036	0.174	1.000	1.000		
5	0.003	0.019	0.996	0.973	1.000	
6	1.000	0.957	0.040	0.051	0.005	1.000

divided into two main groups, N- and Sfc groups with three aspects in each, the difference of landslide incidence between any pair of aspects from the two groups is statistically significant as is indicated by the probability matrix.

The results of this analysis are consistent with the general division of the landslide incidence on N- and Sfc slopes. The pairwise analysis further verifies the division of Nfc and Sfc slopes in general as seen previously in section 2.1.3.

2.5 Conclusions

Landslide incidences on N- and Sfc slopes in measured sections of Battle, Red Deer and Bow valleys in the same geologic formation, the Bearpaw Formation, have been studied to investigate the difference of landslide incidence on N- and Sfc slopes. Past studies have not separated the differences between landslide incidence on N- and Sfc slopes, and hence it is difficult to investigate some more important reasons causing higher landslide incidence.

This study has shown that in the three sections of the Battle, Red Deer and Bow Rivers in the same geologic formation, landslide incidence significantly decreases from the Battle to Red Deer and to Bow Rivers. The average incidences are 96% in the section of the Battle River, 68% in the section of the Red Deer River and 29% in the section of the Bow River. The average landslide incidences mapped in the three sections of the three rivers have given much higher values than the incidences mapped by previous researchers. This may be explained by more detailed and focused mapping in my study area, especially field investigation and verification.

The separation of landslide incidences on N- and Sfc slopes has yielded significant greater incidences on Nfc slopes. The average differences of landslide incidences are 21% in the section of the Red Deer River and 35% in the section of the Bow River. These differences clearly require significant causes of the greater landslide incidences on Nfc slopes.

Various statistical results have showed that landslide incidence is significantly higher on Nfc slopes than on Sfc slopes in the sections of the Red Deer and the Bow Rivers. Pairwise statistical analyses have also showed that an incidence in any 45° sector of the slope aspect in the range of 90-180-270° is significantly less than an incidence in a sector of 45° in the range of 270-360-90°. The difference of the incidences between every pair within one of the ranges is not significantly different.

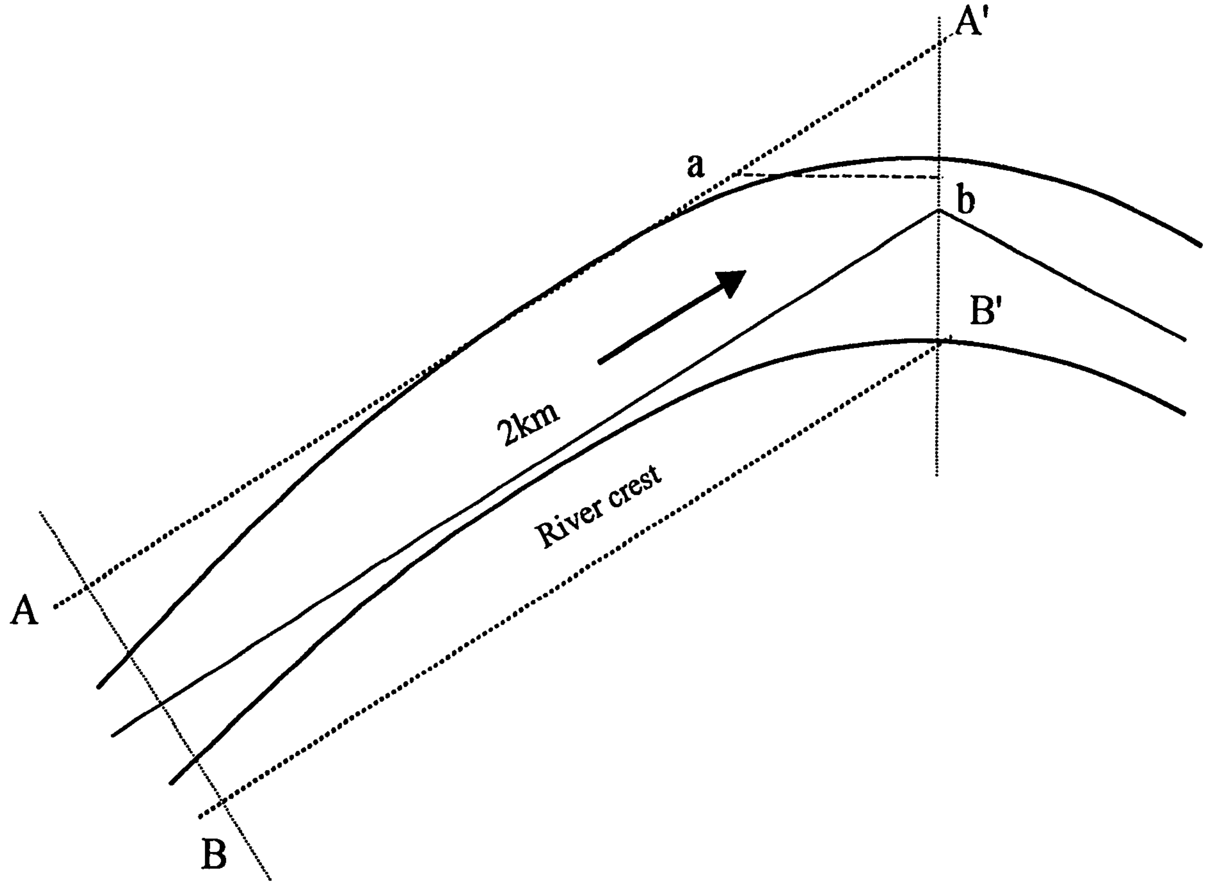
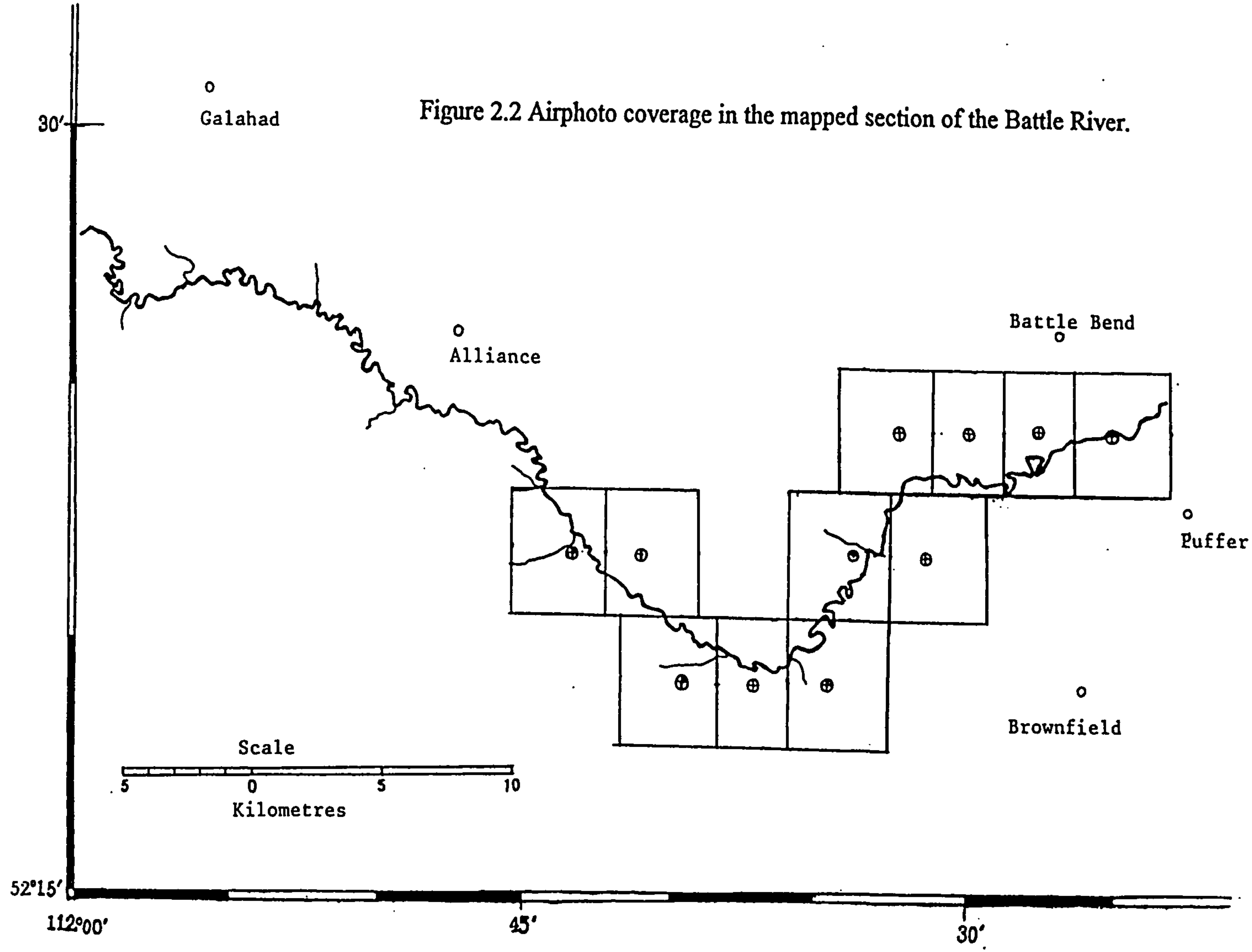


Figure 2.1 Measurement of landslide incidence on valley walls around river meanders.

Figure 2.2 Airphoto coverage in the mapped section of the Battle River.



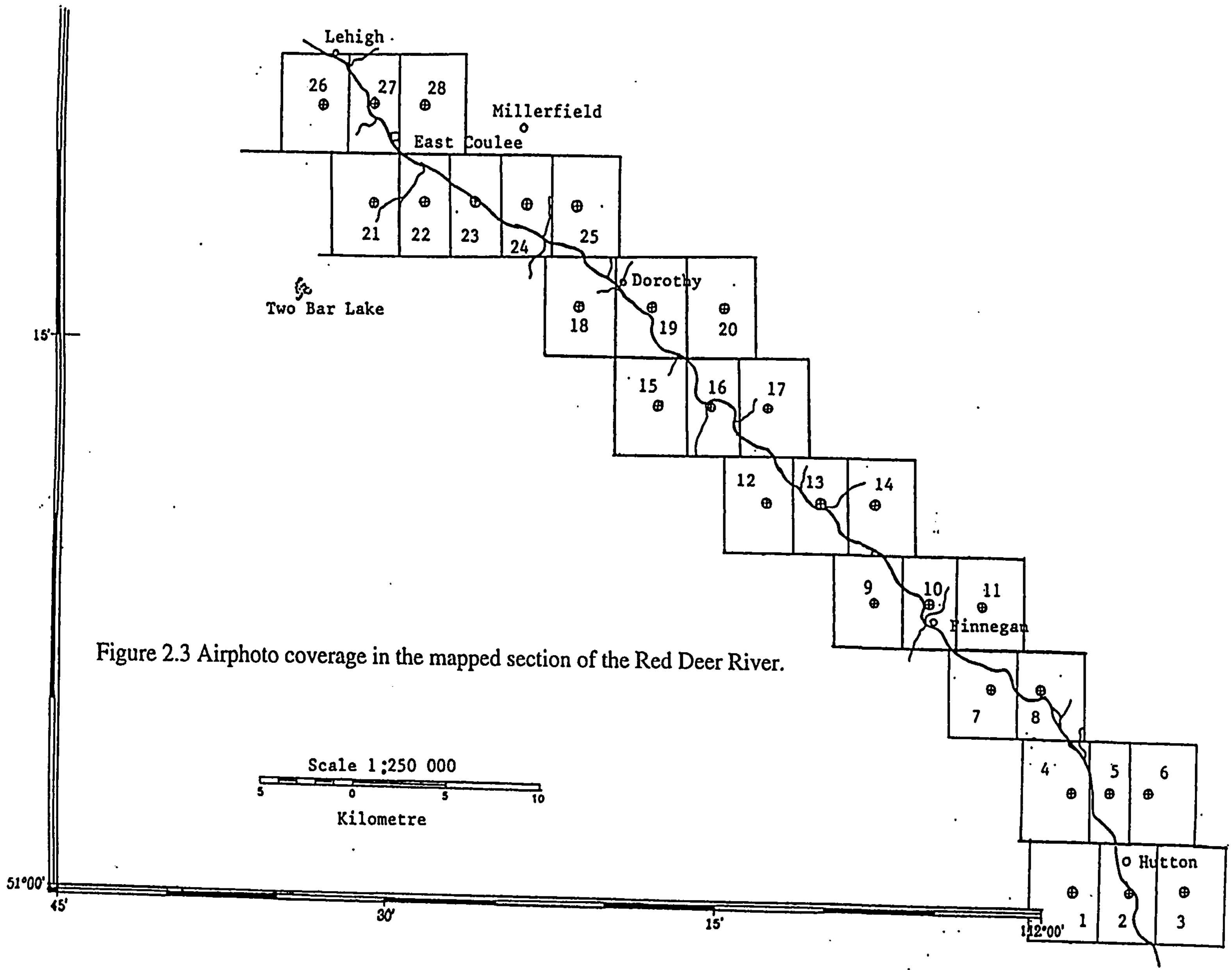


Figure 2.3 Airphoto coverage in the mapped section of the Red Deer River.

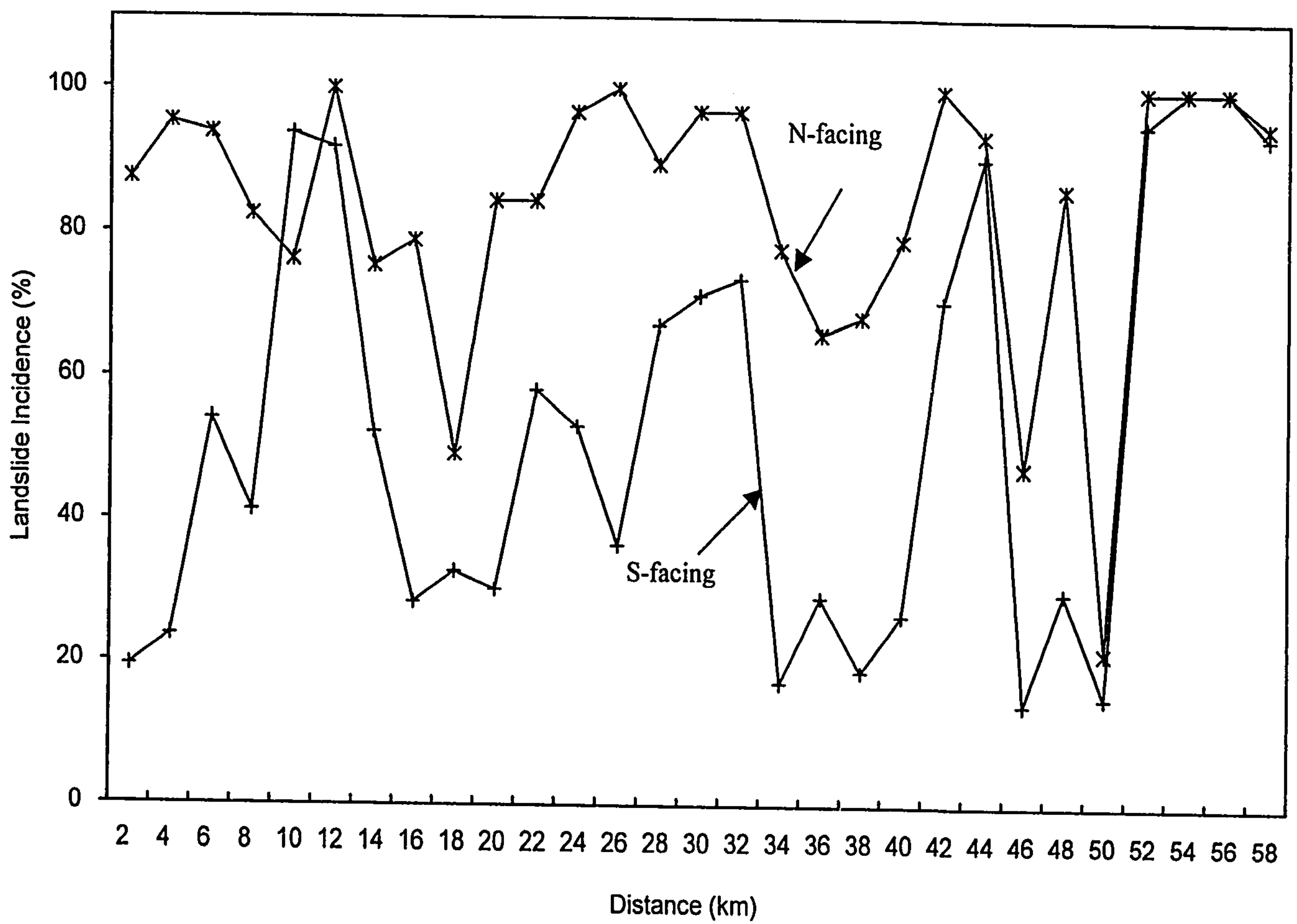


Figure 2.4 Landslide incidence on N- and Sfc slopes in the Bearpaw Formation along the Red Deer River.

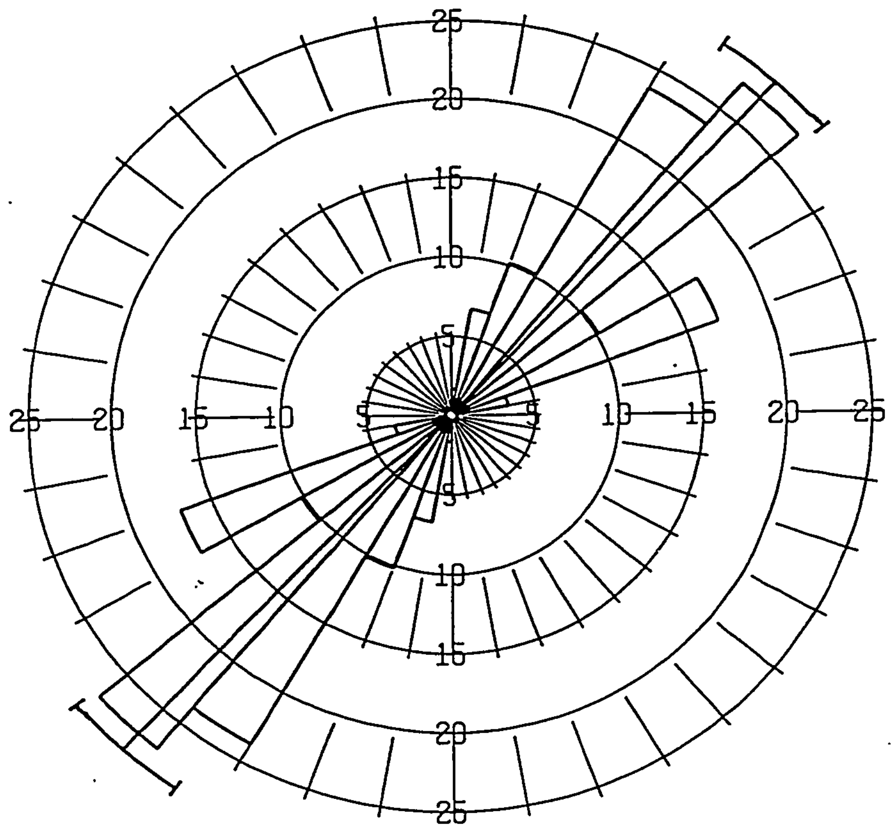


Figure 2.5 Rose diagram of percentage of landsliding aspects in 10 degree intervals on the Red Deer River in the Bearpaw Formation.

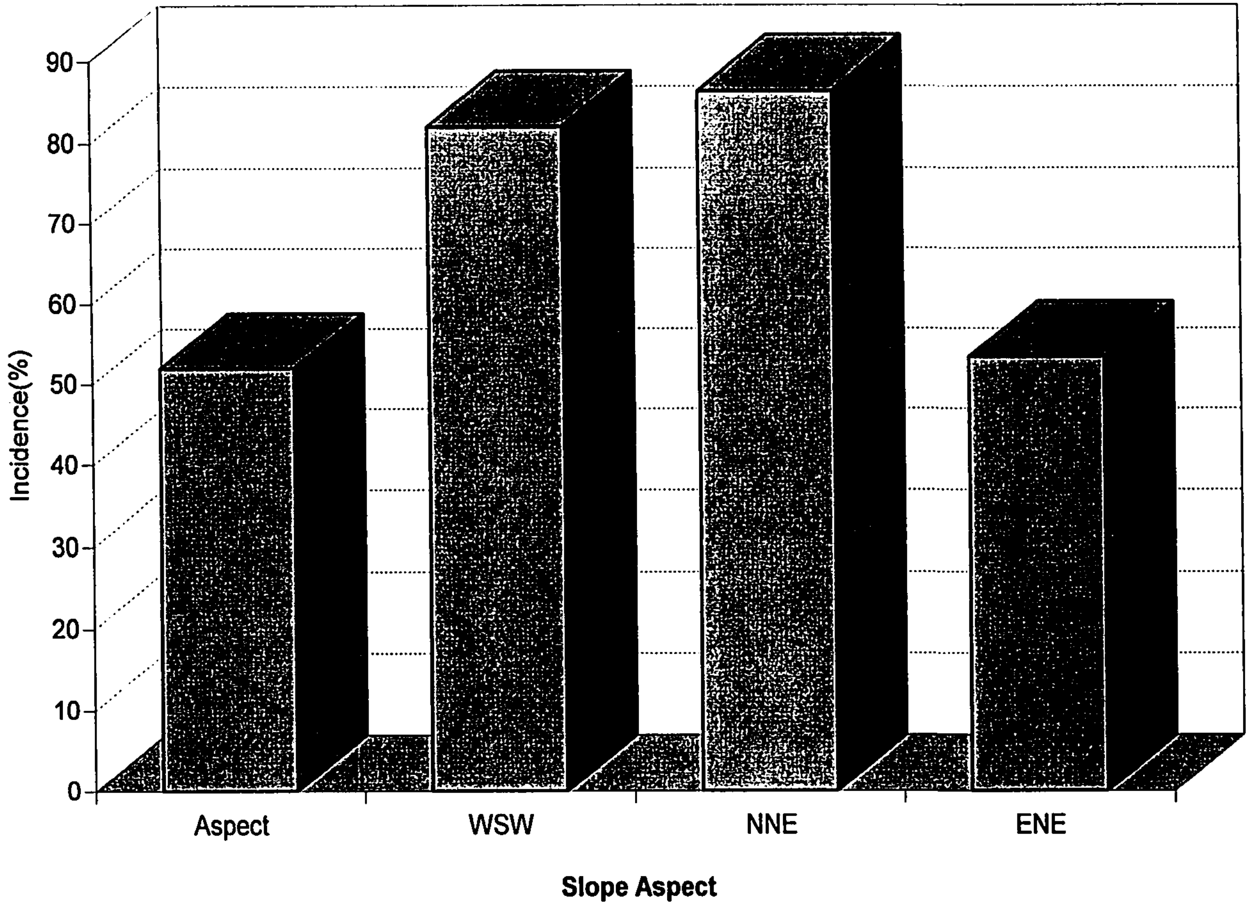


Figure 2.6 The relationship between landslide incidence and slope aspects in the Bearpaw Formation on the Red Deer River.

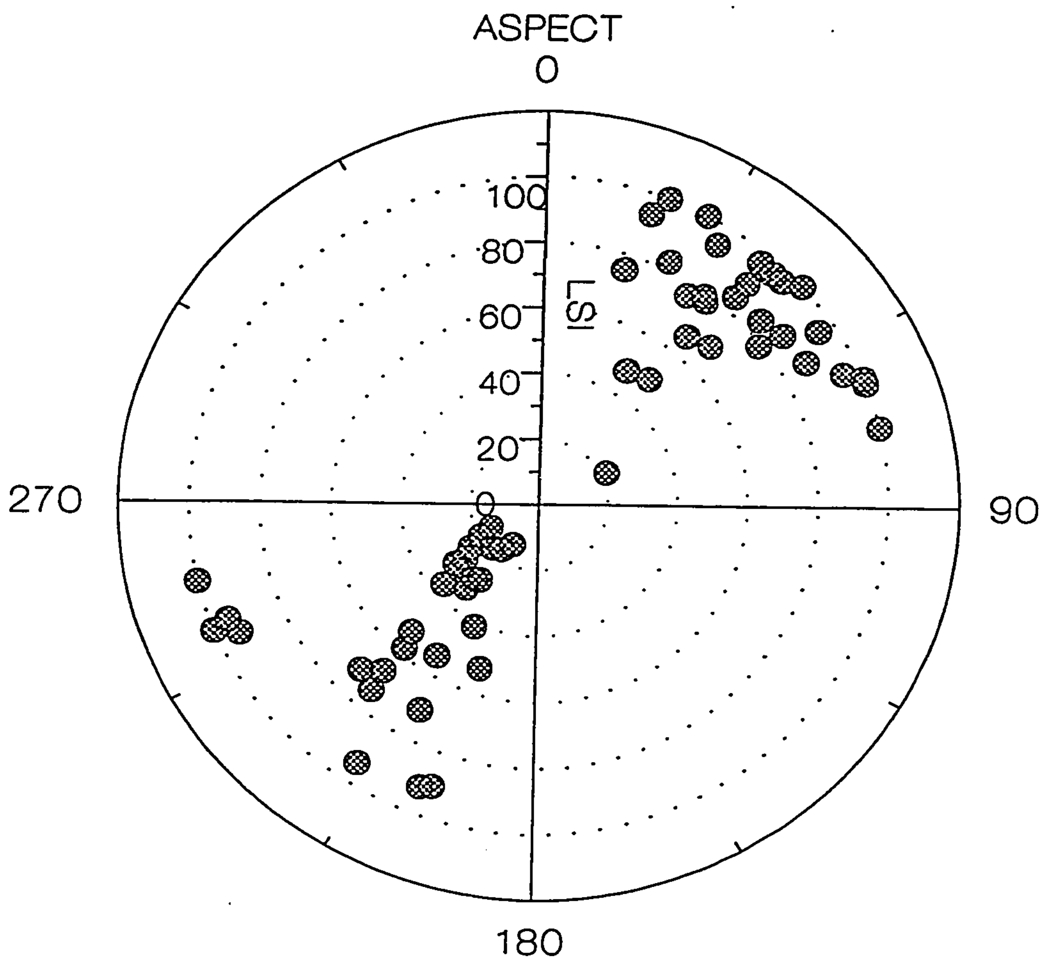


Figure 2.7 Scatter plot of landslide incidence against slope aspects along the Red Deer River in the Bearpaw Formation.

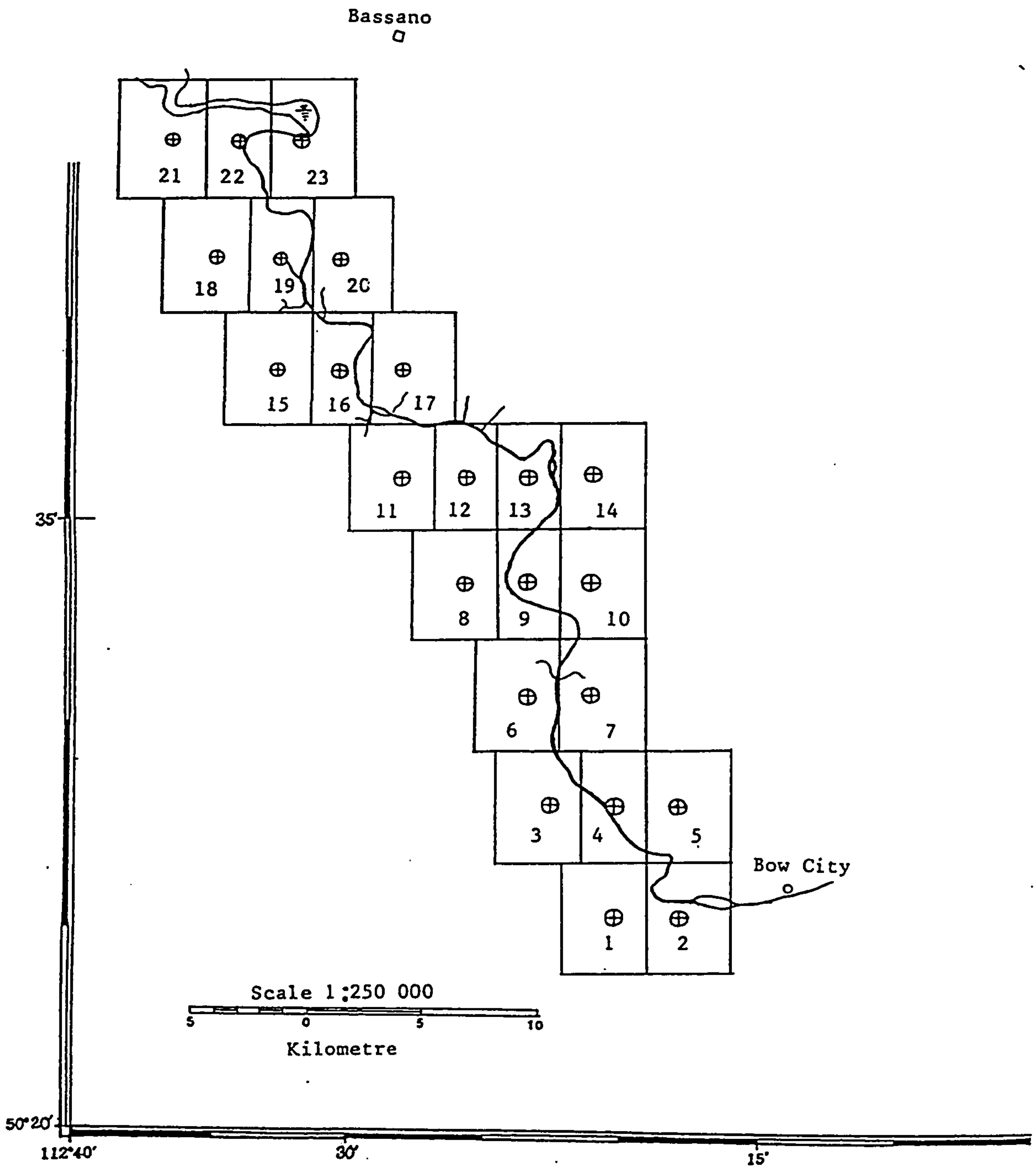


Figure 2.8 Airphoto coverage in the mapped section of the Bow River.

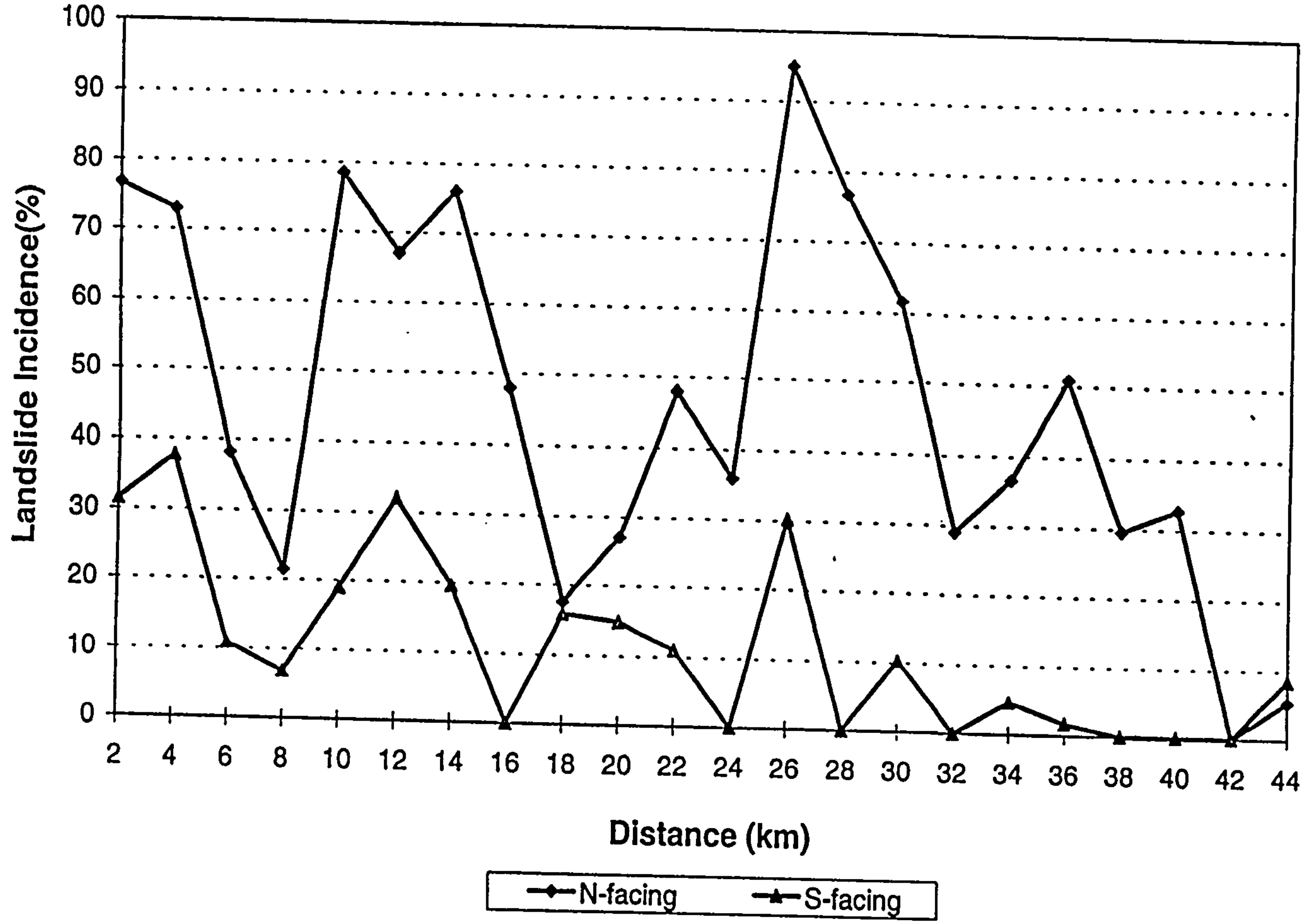


Figure 2.9 Landslide incidence against distance along the Bow River on N and Sfc slopes in the Bearpaw Formation.

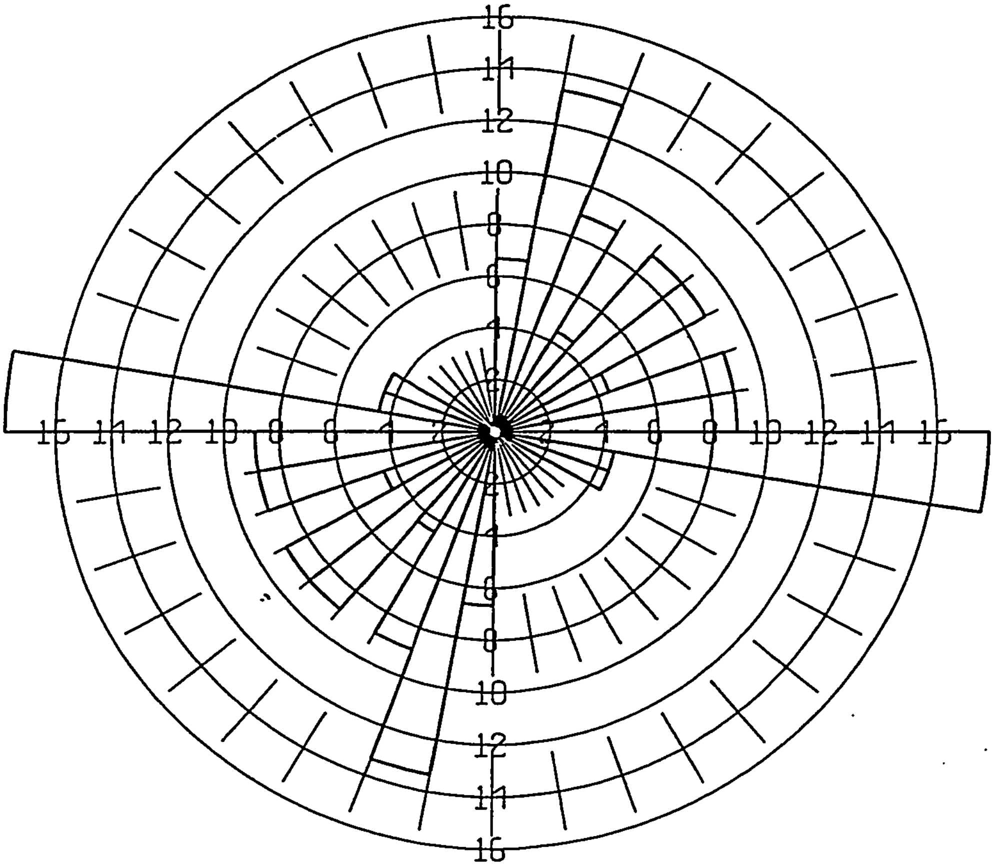


Figure 2.10 Rose diagram of percentage of landsliding aspects in 10 degree intervals on the Bow River in the Bearpaw Formation.

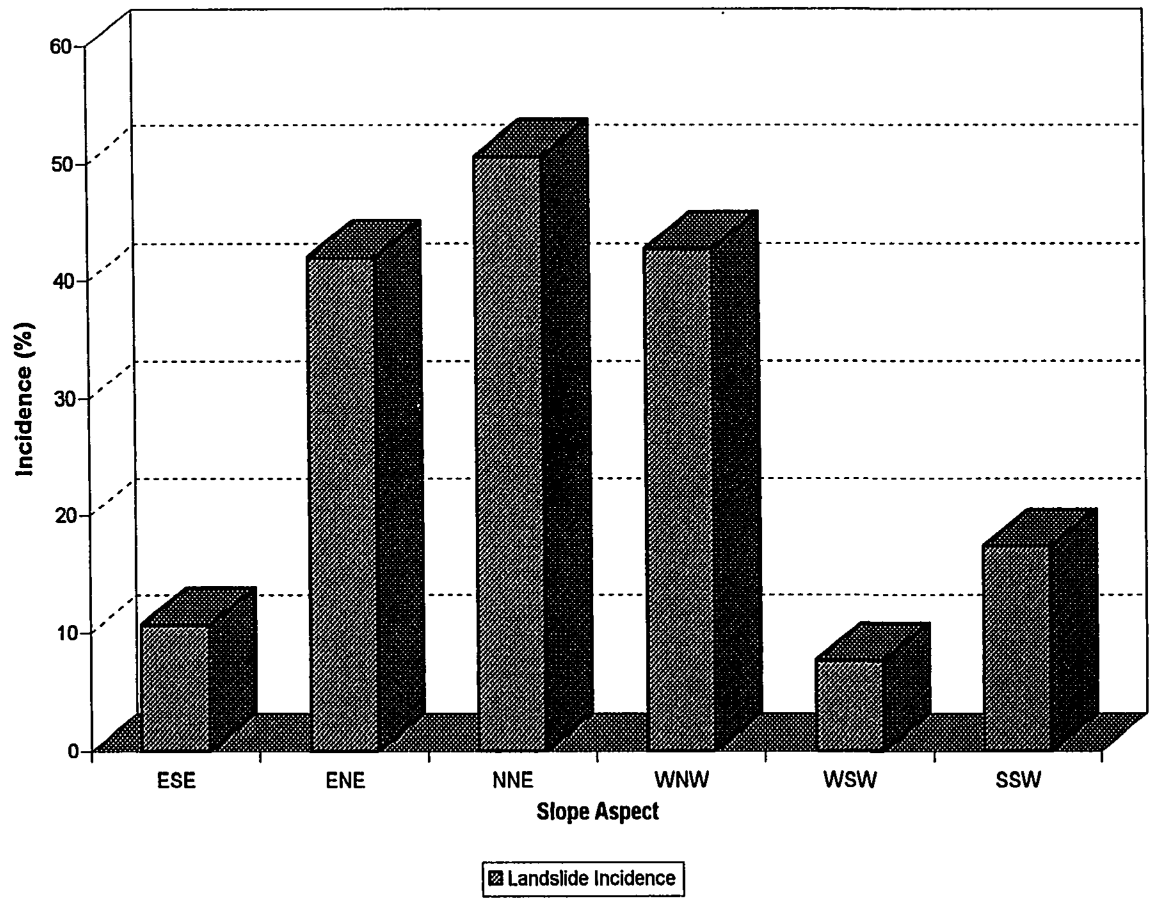


Figure 2.11 The relationship between landslide incidence and slope aspect on the Bow River in the Bearpaw Formation.

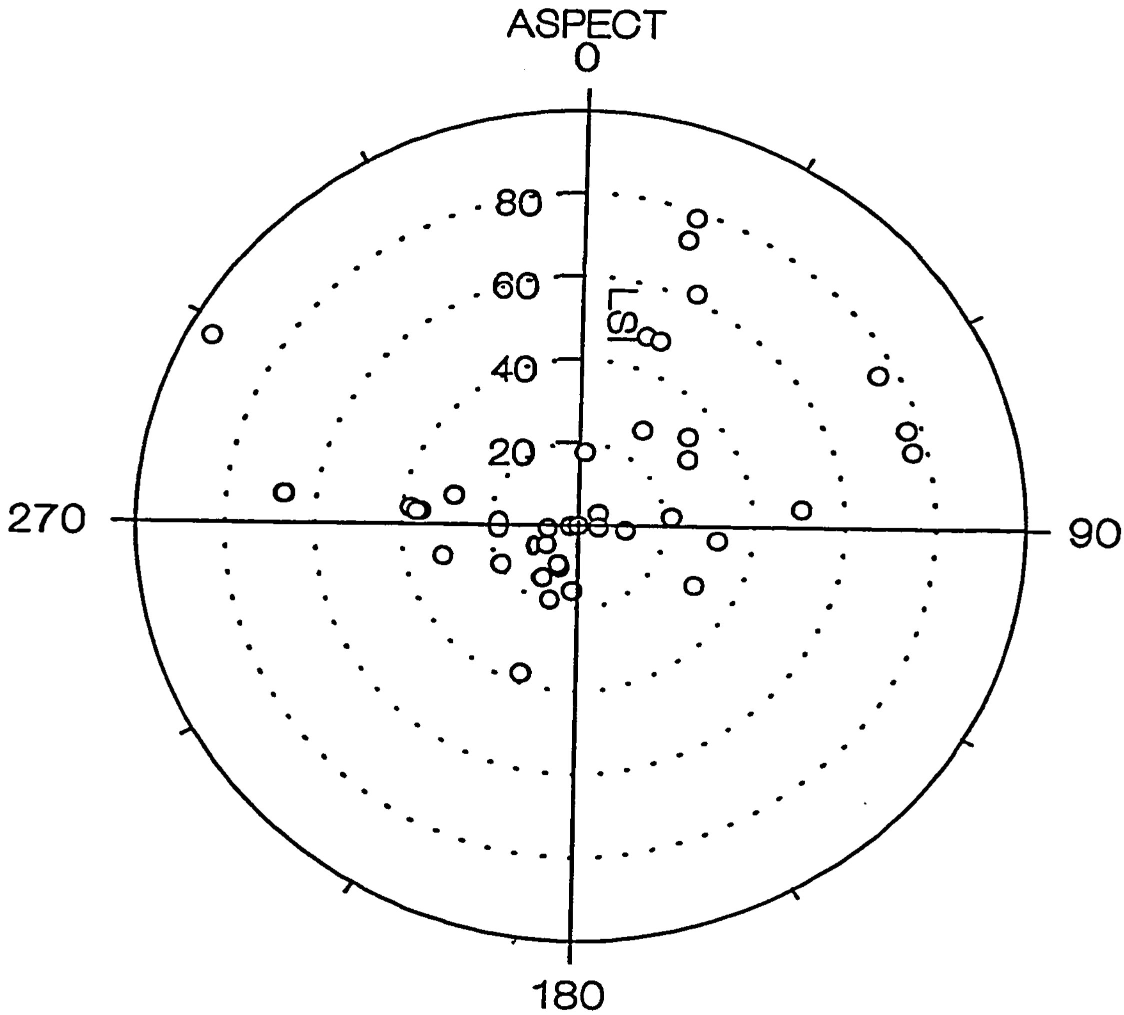


Figure 2.12 Scatter plot of landslide incidence against slope aspects along the Bow River in the Bearpaw Formation.

Chapter 3

Direct Short-wave Radiation Input, Moisture Difference and Their Relationship with Landslide Incidence on North- and South-facing Slopes

3.1 Introduction

Direct short-wave radiation was modelled on the N- and Sfc sloepes in the three river valleys. Based on climatic data from Environment Canada (1994) and observed data from the study area, potential evapotranspiration (*PE*) on slopes was modelled by combining the results of direct short-wave radiation on N- and Sfc slopes. *PE* on the horizontal surfaces was also modelled to compare the difference of *PE* between the sloping surfaces and flat surfaces.

The study of landslide incidence on north and south facing (N- and Sfc) slopes has yielded significantly different results along the Red Deer River and the Bow River in the Bearpaw Formation. Sugden (1973) regards climate and geology as the two main variables influencing the nature of the relationship between process and landform on the Earth's surface. Selby's (1970, p.12) observation is noteworthy: "the two independent variables which are most important in influencing erosion are climate and geology". Since the geology in every 2 km pair of measurements of landslide incidence on N- and Sfc slopes along a river section can be reasonably regarded as homogeneous, the microclimatic differences on N- and Sfc slopes may result in different moisture conditions (Beaty, 1972b) which are possibly the cause of the differences of landslide incidences on N- and Sfc slopes on the three river sections in southern Alberta. Hillslope form varies as a function of aspect-induced topoclimatic variation, and the differences in climate caused by differences in directional exposure are often as great as climatic differences existing between several degrees of latitude (Churchill, 1981).

The orientation preference of slope failures in southern Alberta was reported by Beaty (1972) and Arvidson (1972). Various studies have also projected that climate or microclimate may be the reason to cause slope failures (Thomson and Morgenstern, 1977; Cruden, et al., 1989; Cruden, et al., 1991; Cruden, 1996). Since different slope aspects and declivities receive different intensities of solar radiation (Davenport, 1967; Ferguson, et al., 1971; Ueno, et al., 1989; Cremeans, 1992;Varley, et al., 1996) which in turn affect the different moisture regimes on different facing slopes, the cumulative effect of the moisture differences alters the gross hydrological balances over an extended period of time (Reid, 1973). Topoclimatic differences may be most pronounced in areas of moisture deficiency where aspect-induced differences in moisture conditions are likely more critical than they would be in areas of abundant moisture (Churchill, 1981). Analysis of the cause, the direct short-wave radiation, of the moisture difference is necessary to reveal the potential difference of energy input on N- and Sfc slopes in the study area. The difference of direct short-wave input on N- and Sfc slopes caused by different aspects is the only cause of aspect-induced moisture difference on N- and Sfc slopes if other conditions are the same. Soil moisture difference on differently facing slopes has been studied in different areas (Wolfe, et al., 1943; Gilbert and Wolfe, 1959; Reid, 1973; Churchill, 1981). On the basis of this hypothetical relationship between the radiation and moisture, the direct short-wave radiation on N- and Sfc slopes is modelled in the study area in this Chapter.

In the study area, given specific slope aspects and slope angles on N- and Sfc slopes, direct short-wave radiation can be modelled for a specific time of a year at a specific location. Based on climatic data from Environment Canada (1994) and observed data from the study area, potential evapotranspiration (*PE*) on slopes can also be modelled by combining the results of direct short-wave radiation on N- and Sfc slopes. The modelled results of *PE* on N- and Sfc slopes are compared with the results of the modelled *PE* on horizontal surfaces. Modelled results show a strong relationship between the direct short-wave radiation, *PE* and landslide incidence in the study area. Higher short-wave radiation results in higher *PE*, and higher *PE* results in lower landslide incidence.

3.2 Modelling of extraterrestrial radiation receipts on sloping surfaces

3.2.1 Rationale

Radiation received by a surface is usually the major determinant of its climate (Oke, 1978; Link, 1980). The soil moisture regime reflects, in part, the extractive capabilities of evapotranspiration. The main driving force of the evapotranspiration process is supplied by direct solar radiation (Penman, 1948; Davenport, 1967; Crozier, 1986, Chapter 5; Zaruba, and Mencl, 1969, 1982, pp.33-48; Churchill, 1981; Brunsden, 1984; Doornkamp, 1986, p.10) since land aspect and slope declivity help to determine slope insolation (Shanks, 1950; Ferguson et al., 1971).

There are three components of the radiation input: direct beam (*S*), diffuse (*D*) assumed to be isotropic and long-wave (*L*) radiation (Wilson, 1970; Oke, 1987, Ch. 5; Varley, et al., 1996), the latter independent of the angle at which it strikes the receiving surface. Thus, topographically induced radiation controlled by direct short-wave radiation leads to the variations in energy budget differences across the landscape. The relationship between radiation received by a surface and the incident beam is given by the cosine law of illumination: $S_{slope} = S_i \cos\theta$ (Figure

3.1), where S_{slope} is radiant flux density incident on surface AB; S_i is the radiant flux density; θ, the angle between the direct short-wave and the normal to the surface.

S_i is determined by slope angle, the azimuth angle as well as the zenith angle, Z, of the Sun at a given time and location (Oke, 1978, Ch. 5). Generally, the effect of changing locations from low to high latitude in the northern hemisphere is to decrease the illumination of the Nfc slopes at the compensation of the Sfc slopes. Thus, at high latitudes, small slope or aspect changes may be of considerable practical importance (Oke, 1978).

As it is required for the calculation of potential evapotranpiration (Strong and Leggat, 1992), extraterrestrial solar radiation (direct short-wave radiation) on sloping surfaces is modelled on N- and Sfc slopes of the three valleys. The very simplified model of the direct short-wave radiation on N- and Sfc slopes at local solar noon time can be visualized as Figure 3.2 shows. The flux density on the Nfc slope is $Qn = Si\ cos(\alpha + Z)$, and on the Sfc slope is $Qs = Sicos(\alpha - Z)$, so the potential difference of the flux densities on N- and Sfc slopes is as following

$$Qs - Qn = Si(\cos(\alpha + Z) - \cos(\alpha + Z) \qquad (1)$$

$$\cos(\alpha + Z) = \cos\alpha\cos Z - \sin\alpha\sin Z \qquad (2)$$

$$\cos(\alpha - Z) = \cos\alpha \cos Z + \sin\alpha \sin Z \tag{3}$$

$$Qs - Qn = 2\,Si \sin\,\alpha \sin\,Z \tag{4}$$

Here, the Qn and Qs refer to the flux density of direct short-wave radiation on N- and Sfc slopes, individually; α is slope angle; Z is zenith angle; and Si is the direct short-wave radiation. Equation (4) is derived from Equations (1), (2) and (3). It is the difference in direct short-wave radiation between Nfc and Sfc slopes. From Equation (4) it is clear that the difference increases with the increase of slope angle and solar zenith angle.

3.2.2 Modelling of extraterrestrial radiation on slopes

Extraterrestrial solar radiation on sloping surfaces is required for the calculation of *PE* (AgMet Rating Group, 1985; Strong and Leggat, 1992) on N- and Sfc slopes. The modelled extraterrestrial solar radiation tends to be slightly reduced near the ground surface, but the accuracy for this modelling may be sufficient.

Calculation of short-wave energy flux at the top of atmosphere at a specific time is based on the relation (i.e., Liou, 1980; Henderson-Sellers and Robinson, 1994, Ch. 2)

$$Q_{top} = S(\sin\theta \sin\delta + \cos\theta \cos\delta \cos H) \tag{5}$$

where ,

Q_{top} , is the solar radiation at the top of the atmosphere;

S is the solar constant, 1360 Wm^{-2};

θ, is the latitude;

δ, is the solar declination;

H is the hour angle of the Sun.

On the basis of Q_{top} , the extraterrestrial radiation on a horizontal ground surface can be estimated if attenuation is not considered for this approximate calculation. If combined with the direct beam incident on a slope with specific aspect and slope angle, it can give the radiant flux on the sloping surfaces, from which the potential evapotranspiration (*PE*) can be estimated by using the following calculation (AgMet Rating Group, 1985; Strong and Leggat, 1992):

$$PE = N[-4.95 + 0.144(Tmax) + 0.143(Tmax - Tmin) + 0.1(Q)] \tag{6}$$

where,

PE , potential evapotranspiration;

N, number of days in month;

Tmax, Tmin, the mean maximum and minimum temperatures (°*C*);

Q, extra-terrestrial solar radiation ($MJ/m^2/Day$) taken on the 21st day of the month during summer time. The value on the 21st day is then multiplied by the number of the days in the month to get the monthly value of Q. At a specific location, the Q value changes with time of a day and day of a month, but its yearly value is almost constant at a specific location from year to year because it is the extraterrestrial solar radiation approximated as direct short-wave radiation on ground surfaces without considering its attenuation when passing through the atmosphere. However, Q changes with slope angles and slope aspects considerably if sloping surfaces are applied.

The Agro-Climatic Moisture Index which is used in arable land assessment (Alberta Soils Advisory Committee, 1987) is also applied in this modelling based on formulas developed by the Alberta Soils Advisory Committee (1978):

$$\text{AgM Index} = 0.5(P - PE_{May}) + 1.5(P - PE_{June}) + 2.0(P - PE_{July}) + 1.0(P - PE_{August}) \quad (7)$$

For this modelling, the months in the year of 1992 are used to calculate the direct beam radiation on the basis of the climatic data available from three stations within the three river basins. Calculations of *PE* and Q are conducted on N- and

Sfc slopes of the Battle River, Red Deer River and the Bow River in the study area during the summer (May to August). Six individual variables are involved, slope angle, slope aspect, longitude, latitude, reference longitude in the study area, and Julian days. The summer is from May to August (ie., the growing season) following AgMet RatingGroup (1985) and Strong and Leggat's (1992) definition.

3.2.3 Variables for the calculation of received radiation on valley sides of each river

Since this modelling is a quantitative representation of energy input and *PE* on N- and Sfc slopes, the parameters required to represent the differences of the values on the different slopes are considered to be the averages for a specific river section in the study areas. However, the model can accept any valid variables for slope angle and slope aspect whether they are on Nfc or Sfc slopes. Slope aspect can be from 0 to 360° clockwise, and the slope angle from 0 to near 90° from the horizontal surfaces. Variables chosen for the modelling in the study area are the average slope angles and their corresponding slope aspects for the three river sections.

The slope angles and slope aspects were measured using 1:20, 000 topographic maps for each river section. The measurements were done by systematically measuring slope angles and their aspects on both N- and Sfc slopes following the main river channel downstream. The interval between each measurement following the main river channel is 500 m. The values used for this modelling for each of the three river sections are average values. The measured slope angles are considered to be a little lower than the true angles because the top sections, steep scarps, were excluded from the measurements because the scarps do not consistently exist along each of the three river sections. This small effect decreases the difference of *PE* and direct short-wave radiation on N- and Sfc slopes. In the modelling, the 21st day of each summer month is used in the format of Julian day required by the model for the year. This approach follows that adopted by AgMet Rating Group (1985) and Strong and Leggat (1992) in their classification of ecoregions of Alberta.

The latitude variable required in the modelling is taken at the location at the centre of each river section. Another variable, reference longitude, is the same for the three river sections since the three sections are within the same time zone in the study area. The variables required by the model are listed in Table 3.1. The units of the variables in the format required by the model may not be the standard presentation.

Table 3.1 Variables for direct short-wave modelling on the slopes of valley sides.

River	*Slope angle (degree)*	*Slope aspect* Nfc	Sfc	*Longitude*	*Latitude*
Battle	6.4°	357.8°	176.7°	111.558°	52.364°
Red Deer	11.3°	43.8°	224.0°	112.217°	51.155°
Bow River	14.8°	11.5°	191.5°	112.40°	50.585°
The Reference Longitude is: 113.5°, the middle of the time zone					

Modelling of *PE* requires on monthly average of maximum and minimum temperatures and the extraterrestrial radiation (*Q*). In order to estimate *PE*, the same maximum and minimum air temperatures are used on both N- and Sfc slopes on each river. The maximum and minimum temperatures are taken from climatic stations closest to each river section nearest to the centre of the section. However, this use of the same maximum and minimum temperatures decreases the difference of *PE* on N- and Sfc slopes since in the northern hemisphere, Sfc slopes usually have higher temperatures than on Nfc slopes (Parker, 1952; Wilson, 1970). Soil temperatures follow this pattern too (Brooks, 1959, p.23-70; Swift and Knoerr, 1973; Radke, 1982).

A climatic station was chosen for each of the three river sections. They are Brownfield, Two Bar Lake and Brooks AHRC. The criteria used for the selection of the stations are that first, the station is near the centre of the river section; second, the station has relatively long records (8 to 10 years for each selection); and last, the records adopted at different stations should be for same time interval. The parameters from the stations and the brief description of the stations from Environment Canada (1994) are listed in the following tables 3.2, 3.3 and 3.4.

3.3 Results of radiation modelling

3.3.1 Direct short-wave radiation on N- and Sfc slopes along the Battle River valley

As listed in Tables 3.1 to 3.4, the average slope angle along the Battle River is 6.4°, which is the smallest among the three rivers. Direct short-wave radiation on a horizontal surface is also calculated in order to compare the deviations of the radiation on N- and Sfc slopes from horizontal surfaces. Based on *PE* estimation, each summer month's direct short-wave radiation is modelled by using the Julian day of the 21st of the month in the summer, then timing the number of the days in the month in the model. The modelling results are represented in Figures 3.3 to 3.6 for each summer month. The figures show that, in June, the difference of the

Table 3.2 Climatic data at Brownfield station, the Battle River. Elevation is 747m; period of data used 1980-90; location, 52°20'N 111°28'W.

Table 3.2 Climatic data at Brownfield station, the Battle River. Elevation is 747m; period of data used 1980-90; location, 52°20'N 111°28'W.

Brownfield	*May*	*June*	*July*	*August*
Max (°C)	18.6	21.89	23.7	23.0
Min (°C)	3.7	7.8	9.6	8.6
Max-Min	14.9	14.1	14.1	14.4
Precip(mm)	39.7	94.3	89.9	64.7

Table 3.3 Climatic data at Two Bar Lake station, the Red Deer River. Elevation is 876m; period of data used 1983-90; location, 51°17'N 112°33'W.

Two Bar Lake	*May*	*June*	*July*	*August*
Max (°C)	19.0	22.6	25.3	24.0
Min (°C)	4.8	9.0	10.6	10.1
Max-Min (°C)	14.2	13.6	14.7	13.9
Precip (mm)	45.0	67.0	64.6	49.3

Table 3.4 Climatic data at Brooks AHRC station, the Bow River. Station elevation is 758m; period of data used 1980-90; location, 51°33'N 111°51'W.

Brooks AHRC	*May*	*June*	*July*	*August*
Max (°C)	19.5	23.3	25.5	25.1
Min (°C)	4.4	8.8	10.6	9.4
Max-Min (°C)	15.1	14.5	14.9	15.7
Precip(mm)	39.6	52.7	50.7	37.1

radiation on N- and Sfc slopes is the smallest. Before and after June, the difference gradually increases. Figure 3.7 clearly indicates the overall variation of radiation on the 21st day from month to month during summer time. The modelled results also indicate that the daily radiation difference on N- and Sfc slopes is between 0.5-4.1 $MJ/m^2/Day$ during summer time. This difference should be much larger during the rest of the year because in the summer time, the Sun has the highest solar altitude (Oke, 1987, Chapter 1). Equations (1) to (4) give a simplified relationship between the difference of the direct short-wave radiation and the zenith and slope angles at a specific time.

The results also show that if slopes with an angle of 6.4° faces north and south, significant differences of radiation input on the Nfc and the Sfc slopes can result. This difference suggests why the tree covers on N- and Sfc slopes on the Battle River have a significant difference. This is discussed further in Chapter 4.

3.3.2 Direct short-wave radiation on N- and Sfc slopes along the Red Deer River valley

The same modelling procedures are applied to the N- and Sfc slopes on the Red Deer River, where the average slope angle (11.3°) is higher than the angle on the Battle River. The location of the Red Deer River is further to the south, and the slope aspect is more or less NE to SW; whereas on the Battle River, the slope aspect is almost north-south (357.8°-176.7°). Different parameters will generate different direct short-wave solar radiation scenarios. The modelled results for the summer months are shown in Figures 3.8 to 3.11.

The figures show that, generally, the SE-facing slopes receive much higher radiation than the NE-facing slopes. The NE-facing slopes receive higher radiation than the SW-facing slopes in the morning and much lower radiation in the afternoon. The peaks of the radiation values on N- and Sfc slopes appear at different times, which are controlled by the slope aspect. If the slope aspects had a N-S direction, the peaks should be consistent with the peak of the radiation on a horizontal surface.

Figure 3.12 summarises the radiation variation during summer. It reflects that the daily radiation difference is between 1-6 $MJ/m^2/Day$. This result shows that a 11.3° slope facing north and south on the Red Deer River (more south than the Battle River as well) can result in a higher radiation difference than a 6.4^0 slope facing north and south on the Battle River. It further reflects the importance of slope angle and its aspect, as well as the latitude of the location.

3.3.3 Direct short-wave radiation on N- and Sfc Slopes on the Bow River

The Bow River has the steepest slope (average of 14.8°) compared to the other two. It is the most southerly of the three rivers. The slope angle, aspect and its location dictate the radiation regime. Based on the same approach, the Figures 3.13 to 3.17 represent the radiation difference on N- and Sfc slopes on the Bow River. The daily radiation difference between Nfc and Sfc slopes on the Bow River in the study area is the highest (1.4-9.5$MJ/m^2/Day$) among the three. This difference is potentially a cause of differences in hydrological and geomorphological processes on N- and Sfc slopes in this regsion.

3.4 Discussion

It is evident that aspect and angle of a sloping surface with respect to the solar beam are important variables in determining the radiant energy receipts on a slope. It also follows that the naturally uneven configuration of the landscape produces a wide spectrum of micro-climates, and these have implications for other aspects of the physical environment. Plants can be affected, thereby leading to distinctly different assemblages of flora and fauna on slopes of different angle and aspect, such as the vegetation differences on the Battle River, with its patches of tree and shrubs on Nfc slopes compared to the vegetation on Sfc slopes. Similarly, these differences can often be reflected in the type of land-use especially in agriculture and forestry. All the cultivated fields on the slopes of the Battle River in the study area are located on Nfc slopes; there is a higher coverage of trees on Nfc slopes as well. These are clear examples of the moisture difference on N- and Sfc slopes in a river valley where moisture condition is a limiting factor for use in agriculture.

3.4.1 Modelling results of potential evapotranspiration (*PE*) on N- and Sfc slopes

Oke's (1987, Chapter 1) general energy balance, $Q^* \approx Q_H + Q_E$, shows that the net radiant energy received by a surface (Q^*) contributed by direct short-wave and long-wave radiation is mainly dissipated as both sensible heat (Q_H) and latent heat (Q_E), the latter component referring to energy dissipation by evapotranspiration. Since the indirect radiation (long-wave and diffuse radiation) is isotropic everywhere, the direct short-wave radiation causes most of the difference of moisture conditions on N- and Sfc slopes. The effect of the difference of the radiation on the potential evapotranspiration (*PE*) can be estimated by using the AgMet Rating Group's (1985) formula in southern Alberta since *PE* is directly related to energy absorbed by a surface. Based on the redistribution of direct short-wave radiation on sloping surfaces along the three estimated in Sections 3.3.1 to 3.3.3, it is clear that the radiation differences should result in evapotranspiration differences which in turn should generate differences in the moisture conditions on N- and Sfc slopes.

3.4.2 *PE* modelling on N- and Sfc slopes on the Battle River

PE is estimated during the summer growing season. Beyond the summer growing season perod, evaporation is still occurring on but not transpiration from plants. Here the *PE* is modelled to compare N- and Sfc slopes and also to compare it with Strong and Leggat's (1992) classification on horizontal surfaces.

Table 3.5 represents the estimated *PE* and *(P-PE)* on the N- and Sfc slopes on the Battle River. Precipitation, *P*, is from the Brownfield climatic station during 1980-1990, Environment Canada (1994).

Table 3.5 *PE* and *(P-PE)* on N- and Sfc slopes (mm of water equivalent), the Battle River.

Month	PE_{flat}	PE_{Nfc}	PE_{Sfc}	*Precip*	$(P\text{-}PE)_{flat}$	$(P\text{-}PE)_{Nfc}$	$(P\text{-}PE)_{Sfc}$
May	121.4	117.6	123.7	39.7	-81.7	-77.9	-84.0
June	136.2	135.4	136.9	94.3	-41.9	-41.1	-42.6
July	141.0	137.1	143.2	89.8	-51.2	-47.3	-53.4
August	117.6	110.7	123.5	64.7	-52.9	-46.0	-58.8
Total	516.2	500.8	527.4	288.5	-227.7	-212.3	-238.9

The results show that *PE* on flat surfaces, N- and Sfc slopes are greater than the total precipitation on the Battle River as indicated by negative values in Table 3.5. The difference of *PE* on the Sfc slope is 26.6 mm higher than that on the Nfc slope for the summer period.

(P-PE) represents the potential evapotranspiration deficits or surpluses. In May, *(P-PE)* has the highest deficit; otherwise, the deficit is between 40 to 60 mm per month (Figure 3.18). The difference of *(P-PE)* between N- and Sfc slopes is about 17 mm in the summer months. The total *(P-PE)* on a horizontal surface during summer time on the Battle River is consistent with Strong and Leggat's (1992) results for the Aspen Parkland ecoregion within which the Battle River is located. These results also validate the correctness of the modelling results for the Battle River. The summer precipitation (288 mm from 1980 to 1990) at the station is higher than the summer precipitation (259 mm) in Strong and Leggat's (1992) classification. The difference of the summer precipitation could move other modelled variables away from the standard values used in Strong and Leggat's (1992) classification. One reason is the difference in the time period in which the climatic data were collected to calculate the parameters from the period in which the data used by Strong and Leggat (1992) were collected. The climatic data Strong and Leggat (1992) used were from January 1979 through 31 August 1989, while in this calculation, the data collected were from January 1980 to December 1990.

Another reason is that the precipitation from Strong and Leggat's (1992) classification in the ecoregion of the Aspen Parkland is the average of all the stations within the ecoregion. However, the modelling reported here only uses the data from one climatic station. The higher summer time precipitation in this calculation leads to higher values of *(P-PE)* and Agro-Climatic Moisture Index. However, the differences between the calculated values and the standard values are systematic and uniform. In particular, the differences have no effect on the differences of the calculated values on the N- and Sfc slopes because they are independent of the absolute magnitudes. The other two stations on the Red Deer River and the Bow River may have a similar setting as for the Battle River.

The results also indicate that the Sfc slope has a uniformly higher *PE* deficit than that on the Nfc slope. The total difference during the summer is 26.6 mm higher. This could be an important cause of the vegetation difference and groundwater conditions on N- and Sfc slopes during the growing season. It is clear that the moisture deficit is highest on Sfc slopes, lowest on Nfc slopes and the horizontal surface is between the two (Figure 3.19).

3.4.3 Agro-climatic moisture index on N-and Sfc slopes on the Battle River valley

The values of Agro-Climatic Moisture Index (Alberta Soils Advisory Committee, 1987) which are used in arable land assessment on N-and Sfc slopes and flat surfaces are also estimated for comparison with other rivers as well as with Strong and Leggart's (1992) calculations for flat surfaces. The results (Table 3.6) show that they are very close to Strong and Leggat's (1992) results (-233 on a flat surface) for the Aspen parkland ecoregion. However, the modelled results on N- and Sfc slopes are different enough (about 30 mm difference) to be considered as indication of different ecoregions. The values on the Nfc slope clearly show that it falls into the Low Boreal Mixwood ecoregion in the Boreal Ecoprovince with Climatic Moisture Index of -212.3 mm and Agro-Climatic Moisture Index of –241, in comparison to the corresponding values of -217mm and -265 in Strong and Leggat's (1992) classification. The higher index shows that it is well within this ecoregion or an even wetter region.

If the relative difference of summer precipitation is compared from the Aspen Parkland to Low Boreal Mixwood ecoregions, the difference is about 36 mm (Strong and Leggat, 1992). This comparison gives an indication of how different the moisture could be on N- and Sfc slopes on the Battle River from the modelled results in the study area. The Low Boreal Mixwood ecoregion is on the northern side of the Aspen Parkland ecoregion with relatively higher precipitation than the region on its southern side. This tells us that the N- and Sfc slopes of the Battle River can be in different ecoregions based on the moisture regimes and other modelled variables.

Table 3.6. Agro-Climatic Moisture Index on N-and Sfc slopes and a flat surface on the Battle River.

	Flat Surf.	Nfc slope	Sfc slope
AgM Index (mm)	-258.9	-241.2	-271.6

The *PE*, *(P-PE)* and precipitation are presented in Figures 3.18 and 3.19, which give a picture of the amplitude and variation of *PE* and *(P-PE)* on the Battle River during the summer time. Figure 3.18 shows that the precipitation is about 60-70% of *PE* from June to August, but about 30% in May.

Modelled *PE* on Nfc slopes is obviously less than on Sfc slopes in June, during which the *PE* on N- and Sfc slopes has little difference. It is reasonable to assume that the precipitation received on one slope of a river valley is the same as the precipitation received on the opposite slope across the river. Based on this assumption, the difference of *PE* on N- and Sfc slopes is a solid indication of the difference of moisture conditions that other studies have shown (Radke, 1982; Radke, et al., 1993). The differences of *PE* on N- and Sfc slopes vary with the slope aspect and slope angles at a specific location. Slope aspects are true north and south cause the difference of *PE* on N- and Sfc slopes be the greatest at a specific location. The difference can result in significantly different vegetation coverages and species differences on N-and Sfc slopes as tree covers as will be shown in Chapter 4.

3.4.4 *PE* modelling on N- and Sfc slopes along the Red Deer River valley

The same methods are applied to the Red Deer River on the basis of the variables listed in Tables 3.1 to 3.4. The results are listed in Table 3.7. The climatic variables used for the modelling are from the Two Bar station from Environment Canada (1994).

The results shown in Table 3.7 indicate that consistently higher *PE* on the Sfc slopes than on the Nfc slopes of the Red Deer River. The difference of *PE* between the Nfc and Sfc is the smallest in June, and increases in the months before or after June. For convenience, Nfc and Sfc slopes are used here but, on the Red Deer River, the slopes actually are NE-facing and SW-facing. If the aspects were

Table 3.7 *PE* and *(P-PE)* on flat, N- and Sfc slopes on the Red Deer River.

Month	PE_{flat}	PE_{Nfc}	PE_{Sfc}	*Precip*	$(P\text{-}PE)_{flat}$	$(P\text{-}PE)_{Nfc}$	$(P\text{-}PE)_{Sfc}$
May	119.8	113.3	122.4	45	-74.8	-68.3	-77.4
June	137.0	134.7	137.8	67	-70.0	-67.7	-70.8
July	150.5	144.7	153.4	64.6	-85.9	-80.1	-88.8
Aug	119.2	108.6	127.0	49.3	-69.9	-59.3	-77.7
Total	526.5	501.3	540.6	225.9	-300.6	-275.4	-314.7

true north and south, the difference between N- and Sfc slopes would be much higher than the values in the Table 3.7.

The differences of *PE* or *(P-PE)* between N- and Sfc slopes during summer time are 39.3 mm, while the difference is only 26.6 mm on the Battle River. The difference is not only controlled by slope angle and aspect, but also controlled by latitude. The difference of *PE* on horizontal surfaces between the Battle River and the Red Deer River is about 10 mm, which is the amount of the difference caused only by the difference of location and maximum and minimum temperatures between the centres of the two river sections. If all the climatic conditions on the Battle River and the Red Deer River are the same, the 10 mm higher *PE* on the Red Deer River means that 10 mm higher demand of water on the Red Deer River than on the Battle River in order to keep the soil moisture conditions the same at the two locations. However, the higher water demand and lower precipitation (62.2 mm less of summer precipitation than on the Battle River) on the Red Deer River could only make the area much drier than the Battle River as the vegetation difference will demonstrate in Chapter 4.

The precipitation in Table 3.7 is much less than the *PE* (about 40-50% of precipitation during the summer), which leads to higher moisture deficit (-300.6 mm) on horizontal surfaces in summer time than that on the Battle River (–227.7

mm in Table 3.5). The difference of precipitation between the Battle River and the Red Deer River is about 72.3 mm, which is substantial to vegetation during the summer. The vegetation difference on valley slopes between the two rivers (Chapter 4) is good evidence for the precipitation differences. The potential evapotranspiration deficit (*(P-PE)*) is between 60 to 80 mm on the Nfc slope, and 70 to 90 mm on the Sfc slope. The difference of *(P-PE)* between N- and Sfc slopes is from 10-18 mm in the summer months except in June. Those values show the variation of moisture deficit in summer months. Again, the Sfc slope has the highest moisture deficit during the summer months. The total difference between the N- and Sfc slopes is the same as the *PE* (39.3 mm) on the Red Deer River in the study area. The modelled values are a little higher than the value in Strong and Leggat's (1992) classification as the calculation is based only on one climatic station, not the average of all of the stations in the region. More importantly, the time period in which the values were calculated is not the same as in Strong and Leggat's (1992) calculation (Chapter 3.4.2).

The *PE, (P-PE)* and precipitation presented in Figures 3.20 and 3.21 reflect the overall amplitudes and variations of *PE* and *(P-PE)* on the Red Deer River during summer time. Figure 3.21 shows that the precipitation is about 40-50% of *PE* from May to August, which is about 20% less than that on the Battle River (60-70%).

3.4.5 Agro-climatic moisture index on N-and Sfc slopes along the Bow River valley

The values of the Agro-Climatic Moisture (AgM) Index on flat surface, N-and Sfc slopes are estimated in the same way as those on the Battle River and the Red Deer River. The modelled results (Table 3.8) of AgM Indices indicate that the AgM Index on Nfc slope is about 45 mm more than on the Sfc slope in the section of the Red Deer River. The difference is much higher than the difference on the Battle River (30 mm). The higher differences results from the higher *PE*, steeper slope angles and different slope aspects on the Red Deer River. It also indicates that there would be a higher moisture difference between the N- and Sfc slopes on the Red Deer River than on the Battle River because of higher AgM Indices between the N- and Sfc slopes. To compare AgM Indices on N- and Sfc slopes with the Index on the horizontal surface, the differences of the modelled values are -16 mm on the Sfc slope and 29 mm on the Nfc slope.

Table 3.8. The comparison of AgM Indices on flat, N- and Sfc slopes on the Red Deer River.

	Flat surf.	Nfc slope	Sfc slope
AgM Index (mm)	-384.1	-355.2	-400.2

The parameters modelled on N- and Sfc slopes on the Red Deer River listed in Tables 3.6 and 3.7 show that the differences of the parameters between N- and Sfc slopes are large enough to be considered as different ecoregions in comparison with the difference of the parameters used in Strong and Leggat's (1992) classification. This relative difference of the parameters on N- and Sfc slopes reveals the difference of microclimatic conditions on the N- and Sfc slopes no matter which station in the region is used to calculate the parameters.

3.4.6 Modelling results of potential evapotranspiration (*PE*) on N- and Sfc slopes along the Bow River valley

Consistent application of the modelling procedures to the Bow River gave the results listed in Table 3.9. The precipitation (1980-1988) is from the Brooks ARHC station, Environment Canada (1994).

Table 3.9 *PE* and *(P-PE)* on a flat surface, N- and Sfc slopes on the Bow River.

Month	PE_{flat}	PE_{Nfc}	PE_{Sfc}	*Precip*	$(P\text{-}PE)_{flat}$	$(P\text{-}PE)_{Nfc}$	$(P\text{-}PE)_{Sfc}$
May	126.3	115.2	129.8	39.6	-86.7	-75.6	-90.2
June	144.0	139.8	143.9	52.7	-91.3	-87.1	-91.2
July	152.6	141.8	156.1	50.7	-101.9	-91.1	-105.4
Aug	132.2	121.6	140.0	37.1	-95.1	-84.5	-102.9
Total	555.0	518.4	569.7	180.1	-374.9	-338.3	-389.6

The modelled *PE* and *(P-PE)* (Climatic Moisture Balance) on horizontal surfaces, N- and Sfc slopes on the Bow River in Table 3.9 show that the difference of *PE* or *(P-PE)* between the N- and Sfc slopes is 51.3 mm. Comparing the values on the Battle River (26.6 mm) and on the Red Deer River (39.3 mm) shows the increase from the Battle River to the Red Deer River and to the Bow River is significant, and approximately equally in magnitude. The gradual increase is strong evidence of the climatic and geomorphic factors in controlling the differences of *PE* because the *PE* is controlled by the latitude as well as the slope angles and aspects.

The difference of *PE* on the horizontal surfaces from the Red Deer River to the Bow River is 28.5 mm, which is a big increase in comparison with the increase of 10 mm from the Battle River to the Red Deer River. The big increase of *PE* on the horizontal surfaces reflects one of the important factors, latitude, in the study areas in controlling the moisture conditions which exist.

3.4.7 Agro-Climatic Moisture Index on N-and Sfc Slopes on the Bow River

The modelled Agro-Climatic Moisture (AgM) Indices on a flat surface, N- and Sfc slopes are listed in Table 3.10. The modelled AgM Index on a flat surface

Table 3.10. Agro-Climatic Moisture Index on flat surfaces, N- and Sfc slopes on the Bow River.

	Flat Surf	Nfc slope	Sfc slope
AgM Index (mm)	-479.1	-435.2	-495.5

is –479.1 mm on the Bow River in the study area, while the modelled value on the Red Deer River (Table 3.8) and the Battle River (Table 3.6) on horizontal surfaces is –355.2 and –258.9 mm, respectively. It is clear that the Bow River area has the poorest moisture condition, the Battle River has the best and the Red Deer River is in the middle in terms of Agro-Climatic Indices in the study area. The difference between the Bow River and the Red Deer River is –123.9 mm and between the Red Deer River and the Battle River is -96.3 mm. The difference would be the key reason why the landslide incidences among the three river sections are different (Chapter 2).

The modelled results of AgM Indices on N- and Sfc slopes are also significantly different. The difference is 60.3 mm from the Nfc slope to Sfc slope on the Bow River, while the difference on the Red Deer River is 45 mm (Table 3.8) and on the Battle River is 30.4 mm (Table 3.6). The differences from north to south in the study area gradually increase, and the increase is different in magnitude. The difference might be one of the most important reasons why the landslide incidences on the Nfc slopes on the Red Deer River and Bow River are significantly higher than on the Sfc slopes (Chapter 2).

The *PE*, *(P-PE)* and precipitation are presented in Figures 3.22 and 3.23. These figures give an overall view of the differences of the modelled results on N- and Sfc slopes on the Bow River in the study area as well as their variation from month to month during summer time. The precipitation is only 30-40% of the *PE* on the Bow River. Comparing these values with the values modelled on the Battle River and the Red Deer River shows that precipitation decreases considerably while the *PE* gradually increases from the Battle River to the Red Deer River and to the Bow River.

3.5 Discussion and conclusions

Solar radiation is an important input for many aspects of hydrology, meteorology, and biology (Varley et al., 1996). Although its computation is relatively straightforward for a horizontal surface, in many physical situations, the influence of the topographic characteristics of the slope angle, and its aspect, need to be taken into account.

The variable distribution of solar direct short-wave radiation is the major driving force for the variations in the rest of the energy balance components, thus leading to variations in the local climate on N- and Sfc slopes in the way the modelled results show.

The modelled results of direct short-wave radiation on *PE, (P-PE)* as well as the Agro-Climatic Moisture Index from the three river study areas show that moderate differences of climatic parameters exist between N- and Sfc slopes. These differences may be significant in reference to the criteria of climatic parameters used by Strong and Leggat (1992). Consequently, those differences reflect the differences of moisture regime on N- and Sfc slopes in the study area. In the study area, *PE* on Sfc slopes has higher values than on Nfc slopes. As a result, Sfc slopes should be drier than Nfc slopes, or the Nfc slopes have higher moisture content than on the Sfc slopes. A maximum moisture difference of about 10% between N- and Sfc slopes is described in the Climatic Classification User's Manual (Version 2.0) (Northern Agricultural Research Centre, 1993). The manual also refers to the moisture difference on N- and Sfc slopes as Moisture Reward and Penalty from an agricultural point of view.

The modelled total *PE* on horizontal surfaces, N- and Sfc slopes on the three river sections during summer time is over 500 mm, which is much higher than the total summer precipitation on each of the three rivers. The difference of *PE* between the N- and Sfc slopes on the Battle River during the summer time is 26.6 mm, on the Red Deer River is 39.3 mm and on the Bow River is 51.3 mm.

The difference gradually increases from the north to the south in the study area, which indicates that the difference of moisture conditions between N- and Sfc slopes in the study area increases from north to south. This is consistent with the differences of landslide incidences between N- and Sfc slopes from the Red Deer River to the Bow River.

The modelled total *PE* on horizontal surfaces from the Battle River to the Red Deer River and to the Bow River during summer time is 516.2, 526.5 and 555.0 mm, respectively. The difference of *PE* on the horizontal surfaces from the Red Deer River to the Bow River is 28.5 mm, while the difference of the *PE* from the Battle River to the Red Deer River is 10 mm. The increase of *PE* on the horizontal surfaces reflects one of the important factors, latitude, in the study area in controlling the moisture conditions in addition to the maximum and minimum temperatures at the location.

The modelled AgM Index on a flat surface is –479.1 mm on the Bow River, while on the Red Deer River and the Battle River on horizontal surfaces is –355.2 and –258.9 mm, respectively. It is clear that the Bow River area has the poorest moisture condition, while the Battle River has the best and the Red Deer River is in the middle in terms of Agro-Climatic Indices in the study area during summer time. The difference between the Bow River and the Red Deer River is –123.9 mm and between the Red Deer River and the Battle River is 96.3 mm. The change of AgM

Indices on differently facing slopes from the Bow River to the Red Deer River and to the Battle River in the study area is shown in Figure 3.24. Figure 3.24 indicates considerable changes of AgM Indices from Nfc slopes to horizontal surfaces and to the Sfc in the study area. The differences may be an important reason why the landslide incidences among the three river sections are significantly different because other conditions are the same or similar.

The modelled results of AgM Indices on N- and Sfc slopes are also significantly different. The difference is 60.3 mm from the Nfc slope to Sfc slope on the Bow River, while the difference on the Red Deer River is 45 mm and on the Battle River is 30.4 mm. The differences from north to south in the study area gradually increase with different magnitudes, increasing the moisture deficit from north to south across the study area. The differences are probably the most important reason why the landslide incidences on the Nfc slopes on the Red Deer River and Bow River are significantly higher than on the Sfc slopes.

Direct short-wave radiation, *PE*, and AgM Index (Agro-Climatic Moisture Index) are modelled only in the prime growing season, during which the sun has the highest zenith angle, and therefore the radiation difference on N- and Sfc slopes is at the minimum. Higher radiation differences on N- and Sfc slopes should occur if the time period is extended beyond August or May, i.e., the difference of direct short-wave radiation in September on flat, N- and Sfc slopes on the Bow River (Figure 3.25) where the Sfc slope receives almost two times the radiation the Nfc slope receives.

If the short-wave radiation on N- and Sfc slopes is considered beyond summer months, the difference of the short-wave radiation on N- and Sfc slopes should be much higher than the difference in summer time. Other factors, such as lengths of snow-cover retention, vegetation and runoff may also contribute to the moisture difference on N- and Sfc slopes

The modelled *PE* and AgM Indices should be considered as minima because the maximum and minimum temperatures on N- and Sfc slopes are considered as the same in the modelling but studies have shown that Sfc slopes have higher temperatures than Nfc slopes. Such higher temperatures increase evaporation when moisture is available.

Solar radiation difference on N- and Sfc slopes is the primary cause for the variation in the local climate. Hydrologic activity is likely to vary as a result of different rates of evapotranspiration, and lengths of snow-cover retention. The persistence of this is frequently reflected in studies of vegetation distribution (Henderson-Sellers and Robinson, Ch. 6, 1994).

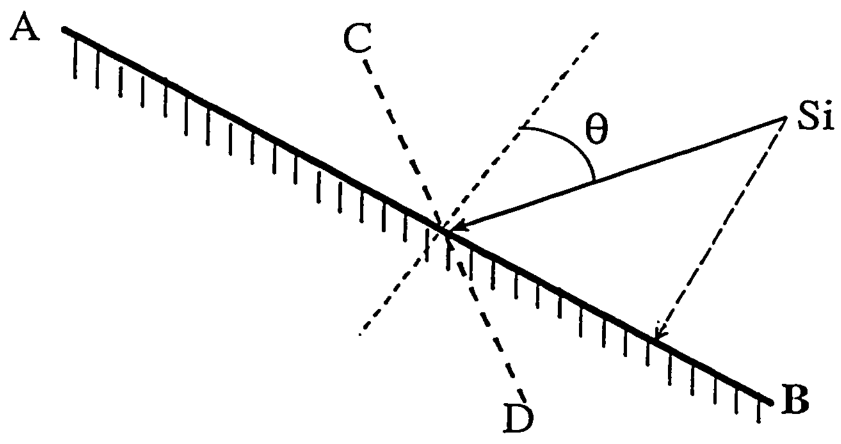


Figure 3.1 Direct short-wave radiation on sloping surface.

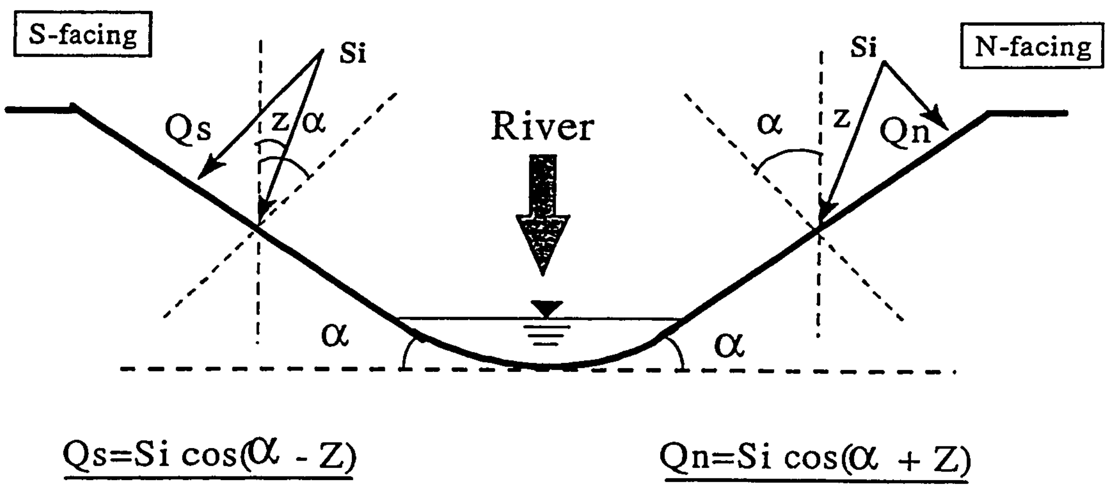


Figure 3.2 Simplified model of direct short-wave radiation on N and Sfc slopes.

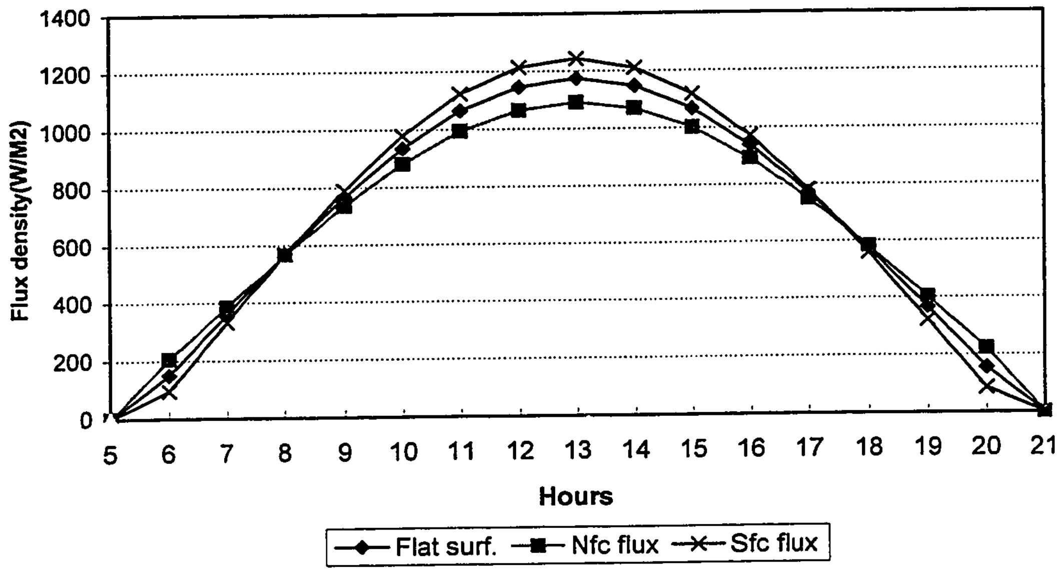


Figure 3.3 Direct short-wave radiation on flat, N and Sfc slopes of 6.4 degrees on the Battle River, May 21, 1992.

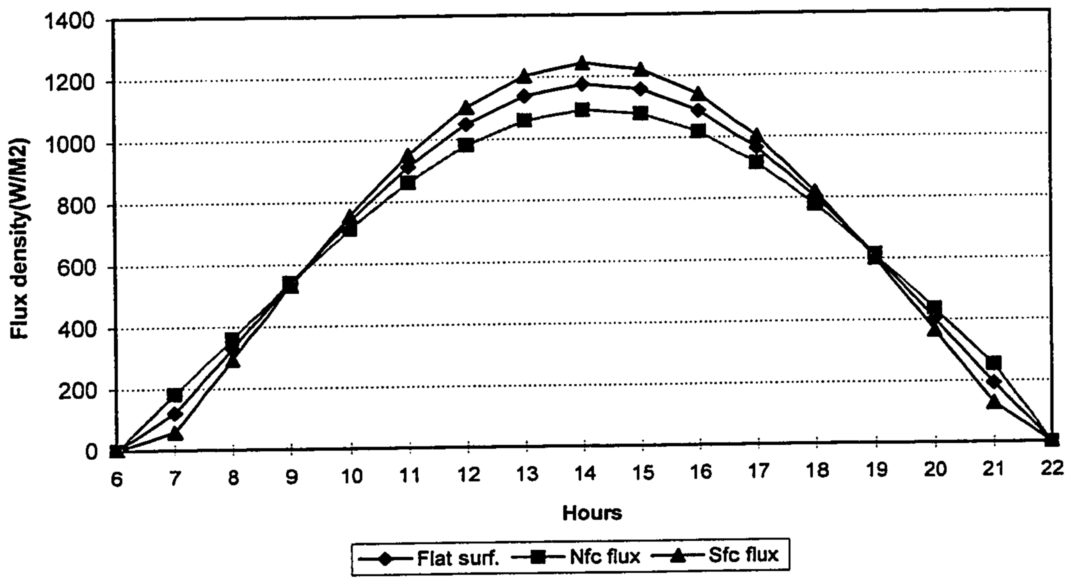


Figure 3.4 Direct short-wave radiation on flat, N and Sfc slopes on the Battle River, June 21, 1992.

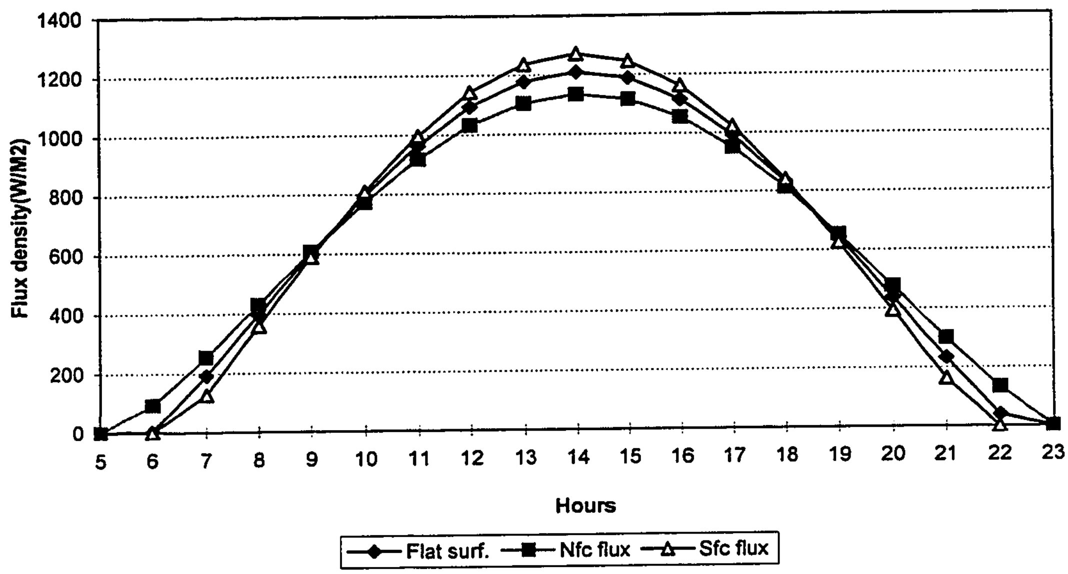


Figure 3.5 Direct short-wave radiation on flat, N and Sfc slopes on the Battle River, July 21, 1992.

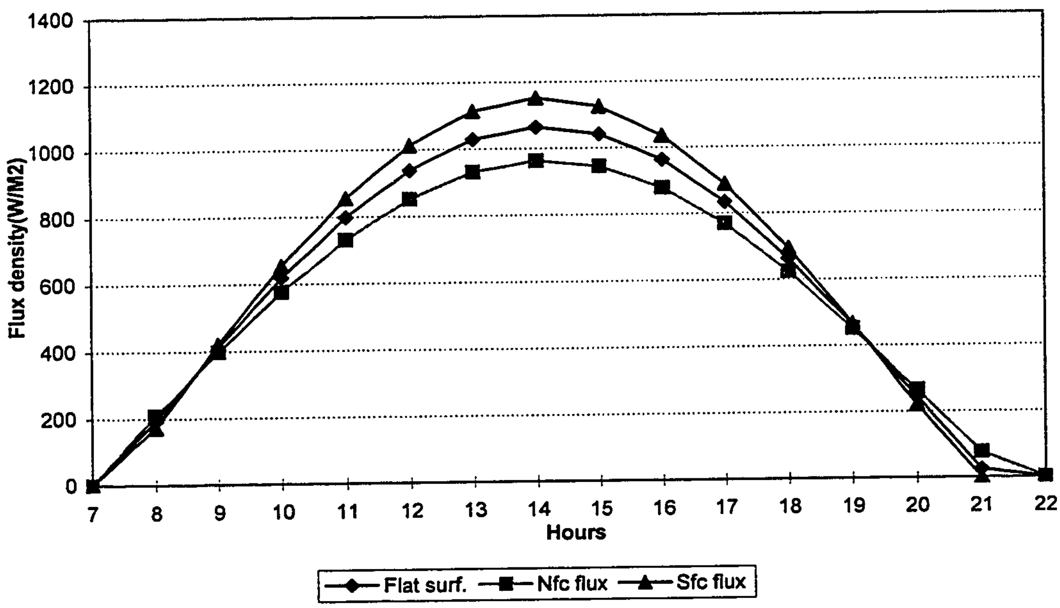


Figure 3.6 Direct short-wave radiation on flat, N and Sfc slopes of 6.4 degrees on the Battle River, August 21, 1992.

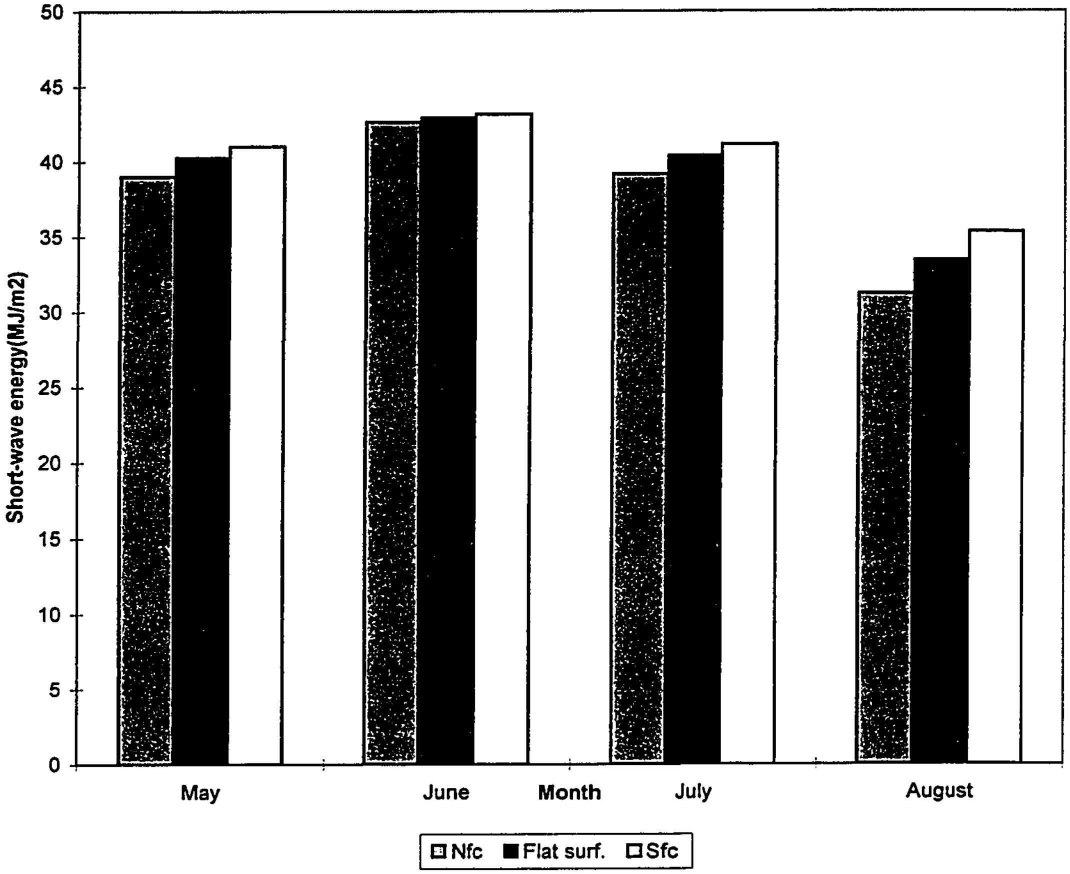


Figure 3.7 Total energy input from direct short-wave radiation on flat, N and Sfc slopes from 21 May to 21 August, 1992, on the Battle River

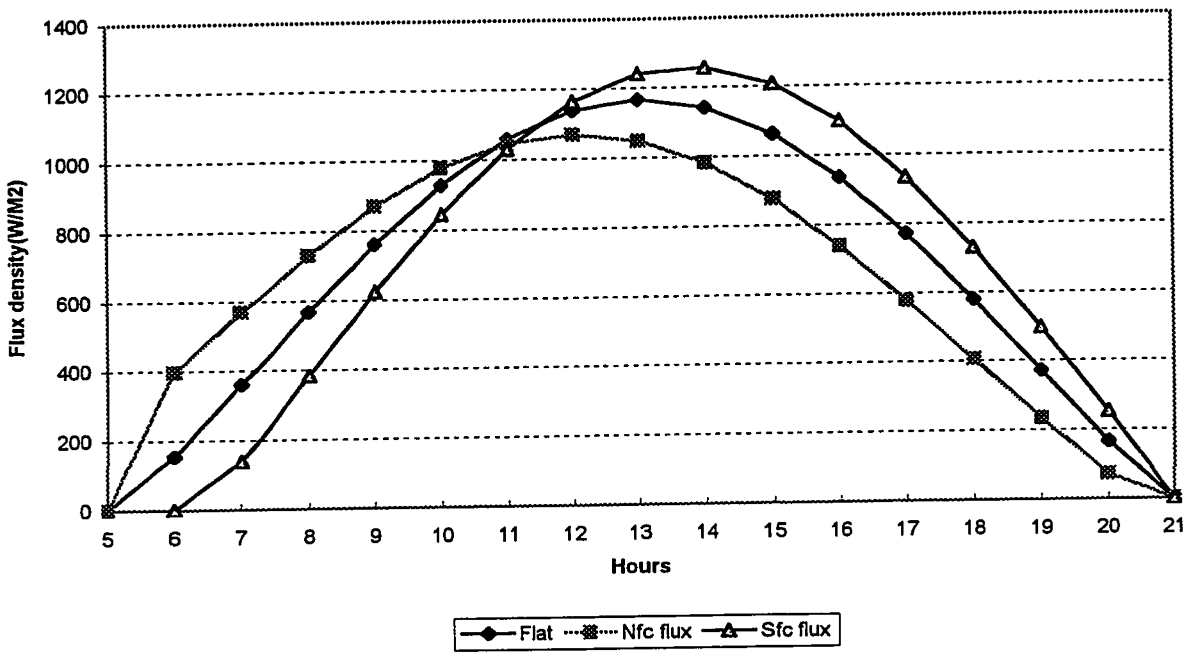


Figure 3.8 Direct-short wave radiation on flat, N and Sfc slopes on the Red Deer River on May 21, 1992.

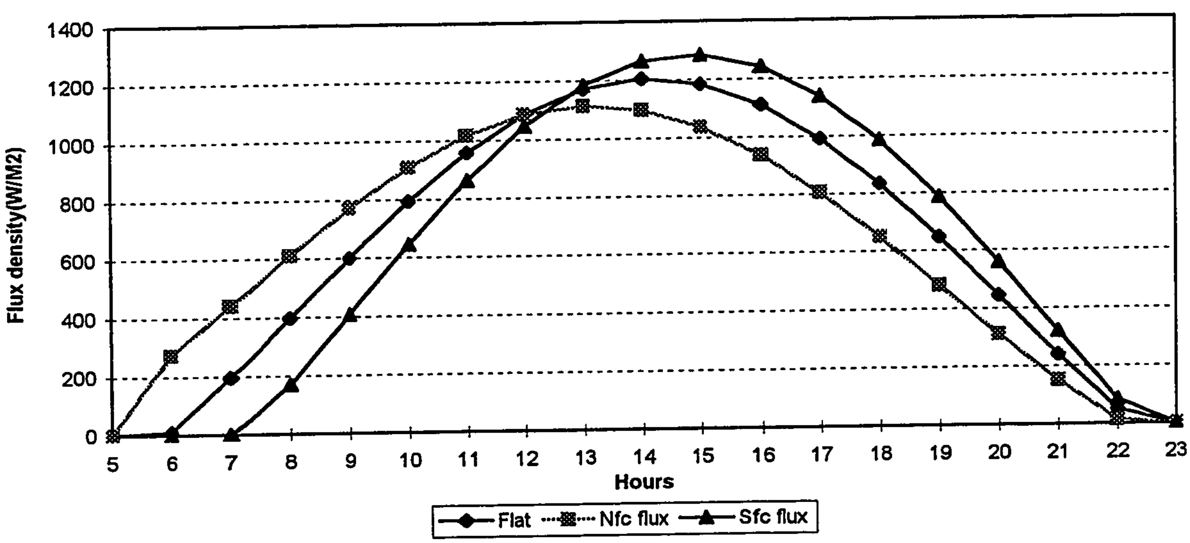


Figure 3.9 Direct-short wave radiation on flat, N and Sfc slopes on the Red Deer River on June 21, 1992.

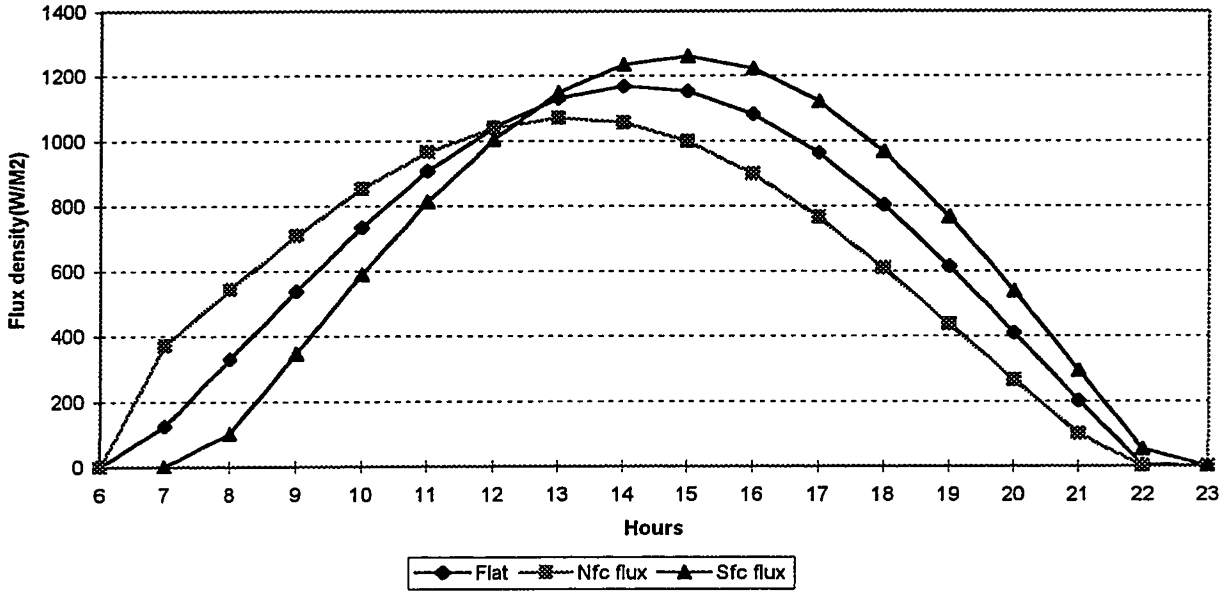


Figure 3.10 Direct short wave radiation on flat, N and Sfc slopes on the Red Deer River on July 21, 1992.

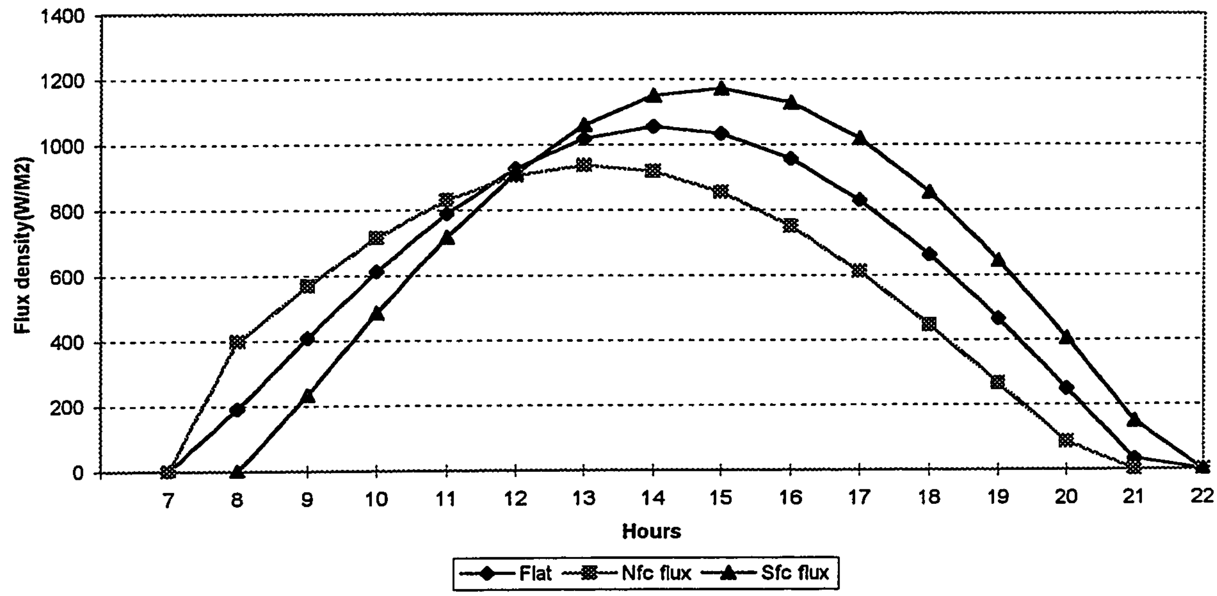


Figure 3.11 Direct short wave radiation on flat, N and Sfc slopes on the Red Deer River on Aug. 21, 1992.

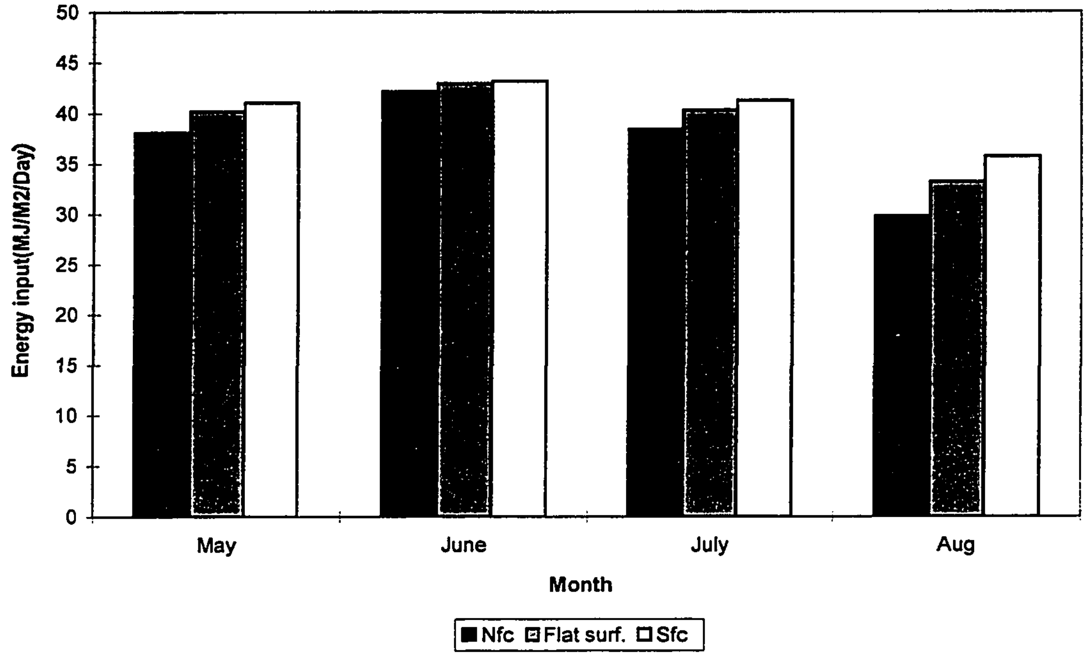


Figure 3.12 Total direct short-wave radiation difference from May to August, 1992 on flat, N and Sfc slopes on the Red Deer River.

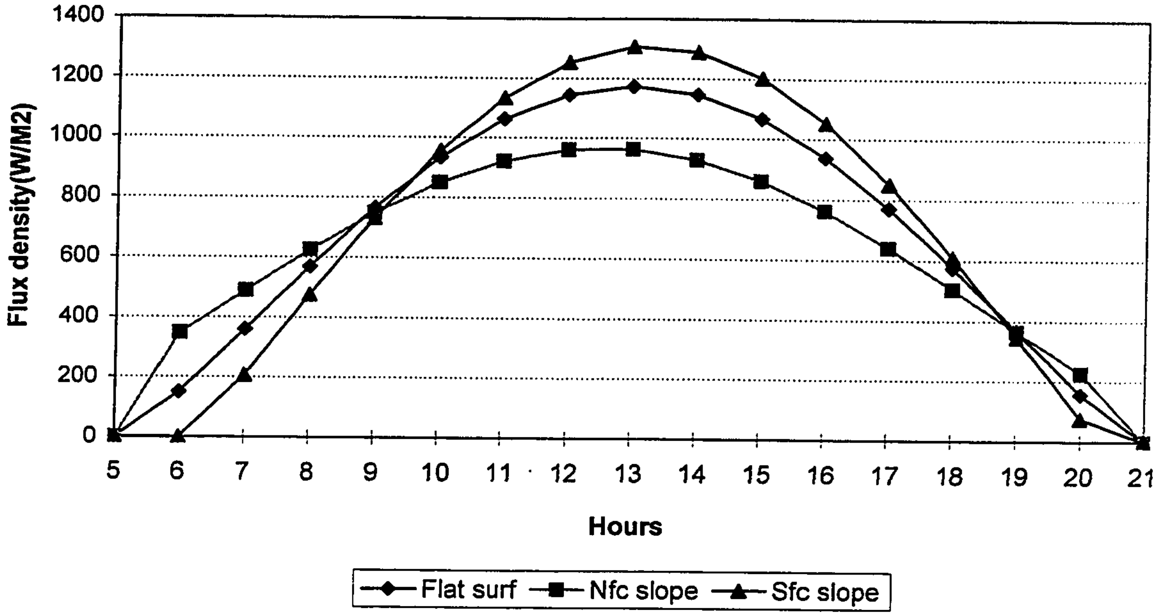


Figure 3.13 Direct short wave radiation on flat surface and on N and Sfc slopes of 14.8 degrees on the Bow River on May 21, 1992.

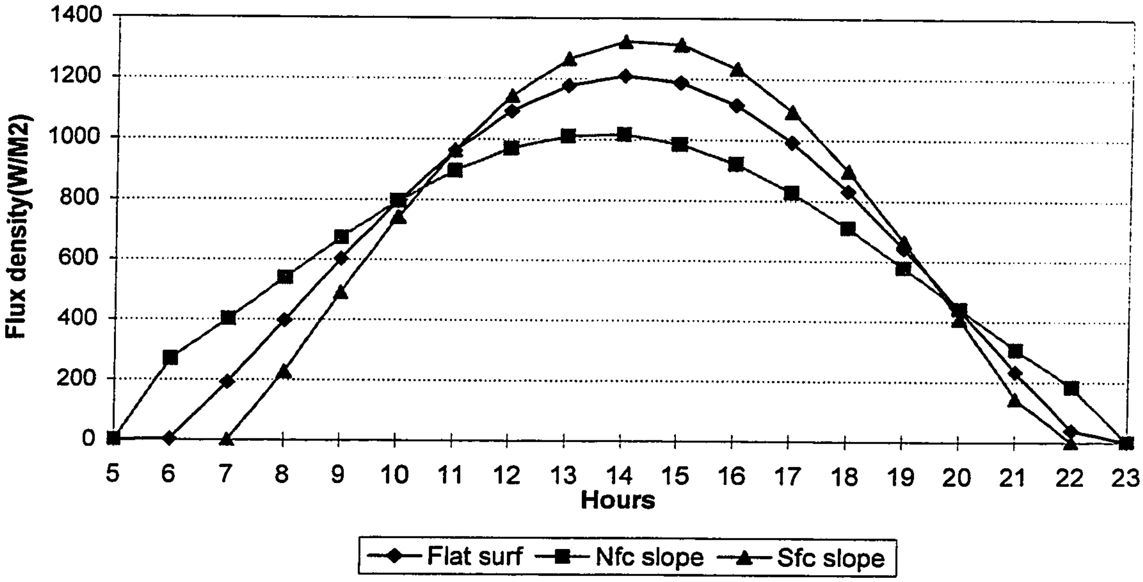


Figure 3.14 Direct short wave radiation on flat surface and on N and Sfc slopes of 14.8 degrees on the Bow River on June 21, 1992.

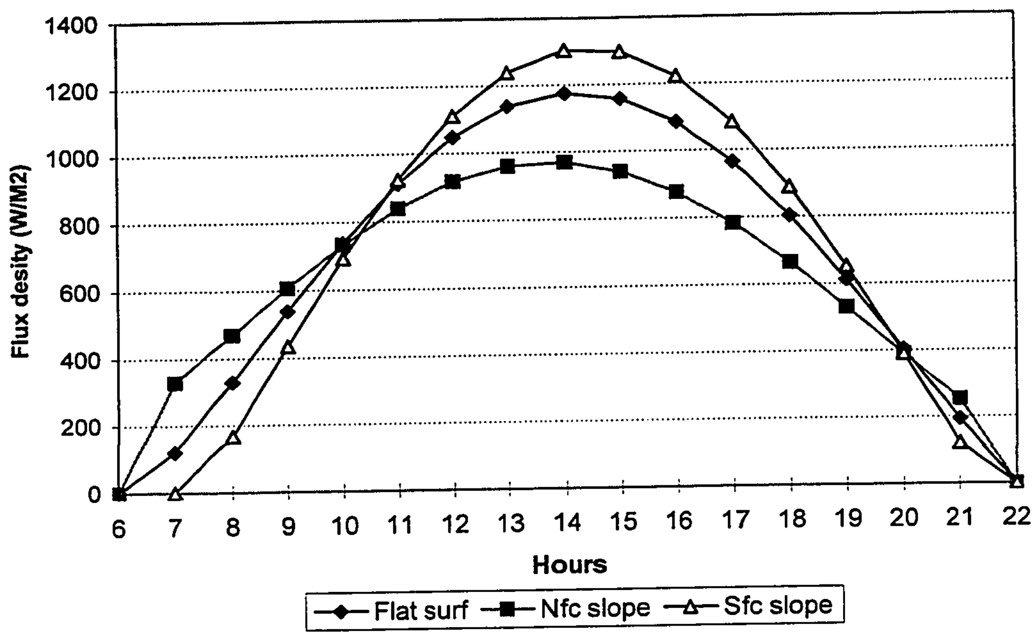


Figure 3.15 Direct short wave radiation on flat surface and on N and Sfc slopes of 14.8 degrees on the Bow River on July 21, 1992.

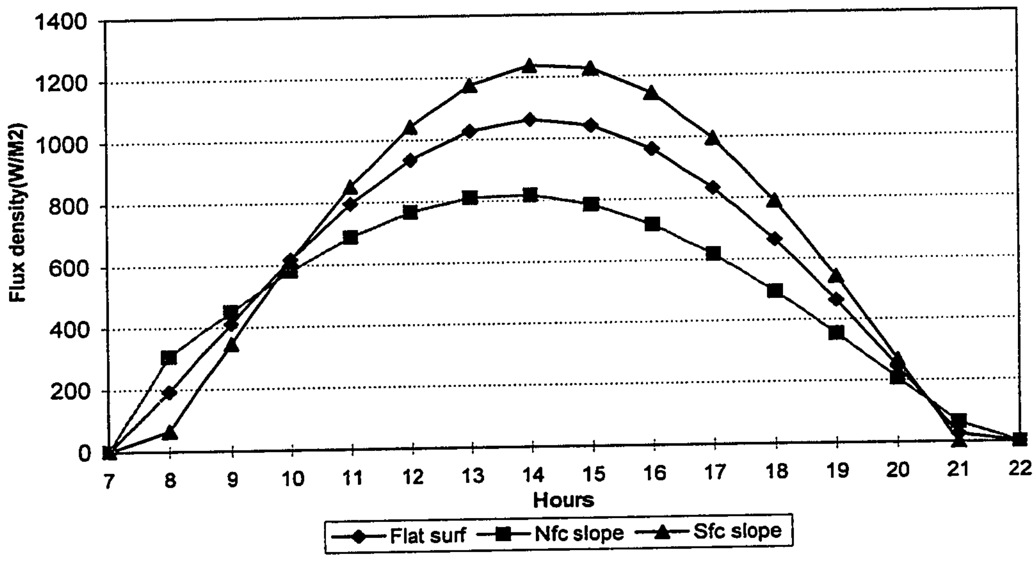


Figure 3.16 Direct short wave radiation on flat surface and on N and Sfc slopes of 14.8 degrees on the Bow River on Aug. 21, 1992.

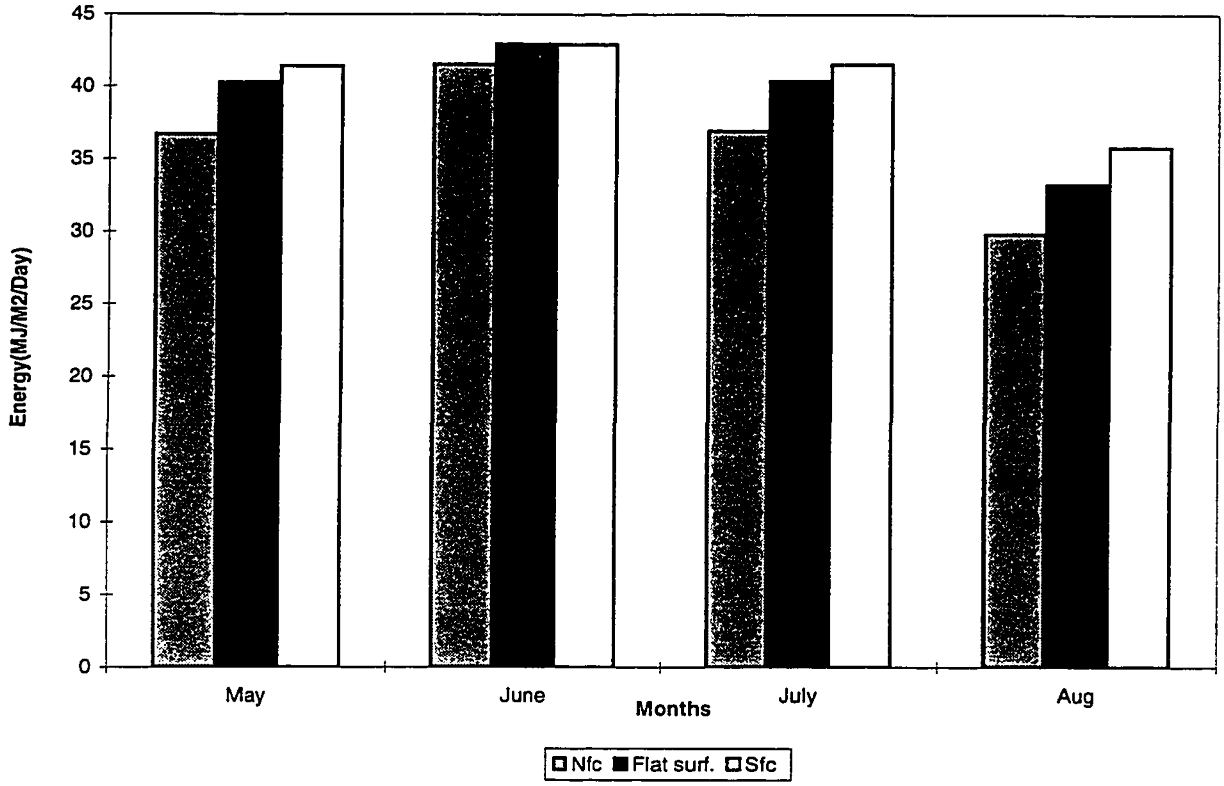


Figure 3.17 Calculated direct short-wave radiation on flat, N and Sfc slopes on the Bow River from May to August, 1992.

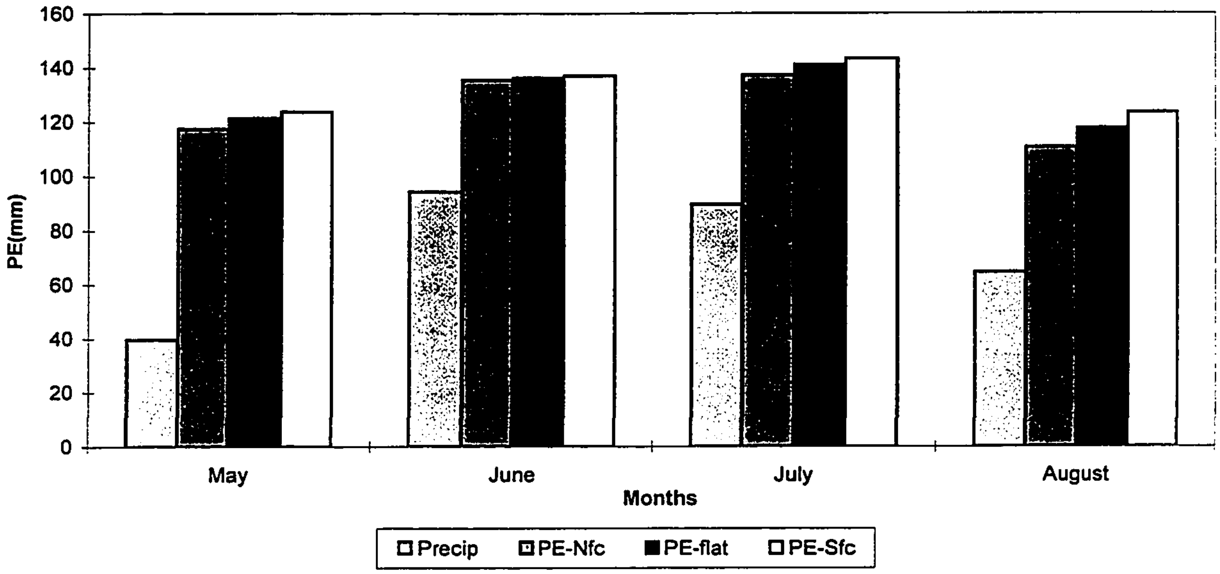


Figure 3.18 PE on flat surface, N and Sfc slopes on the Battle River from May to August, 1992.

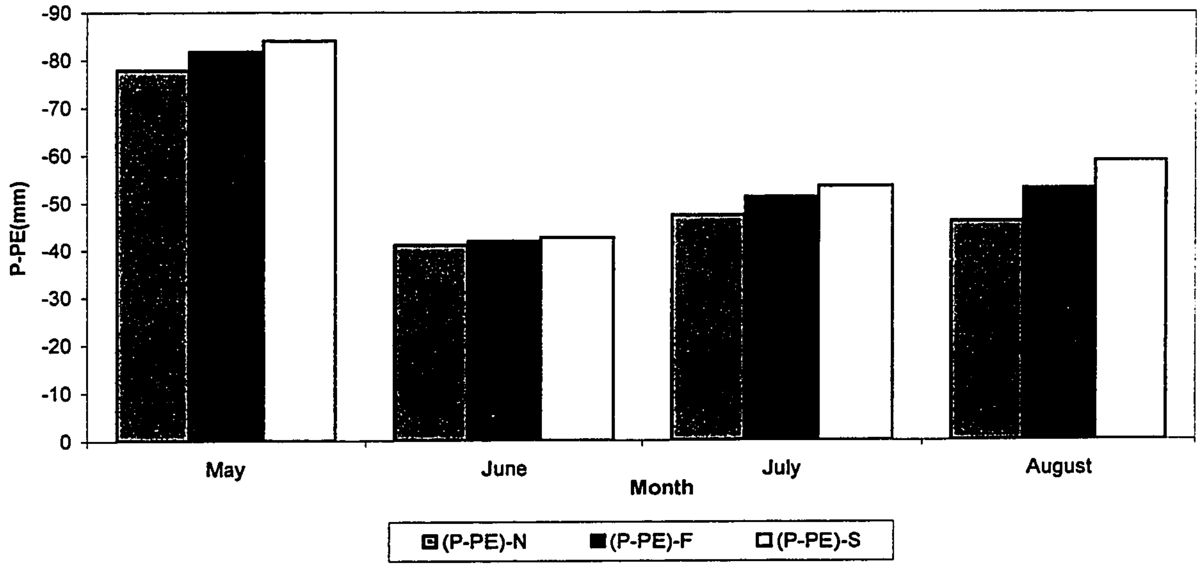


Figure 3.19 P-PE on flat, N and Sfc slopes on the Battle River from May to August, 1992 at Brownfield station.

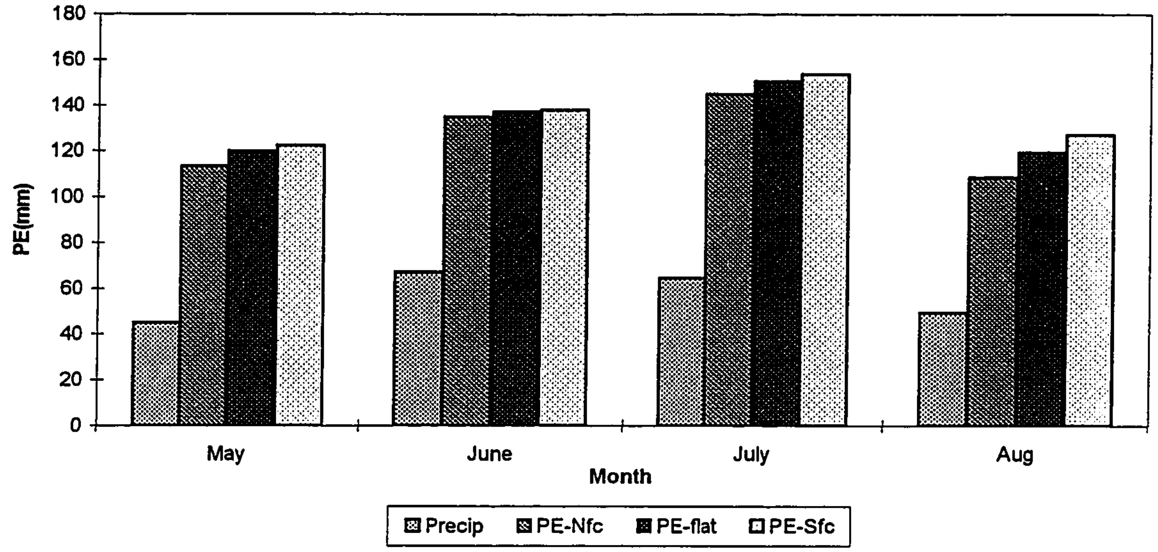


Figure 3.20 PE on flat surface, N and Sfc slopes and precipitation from May to August, 1992 on the Red Deer River.

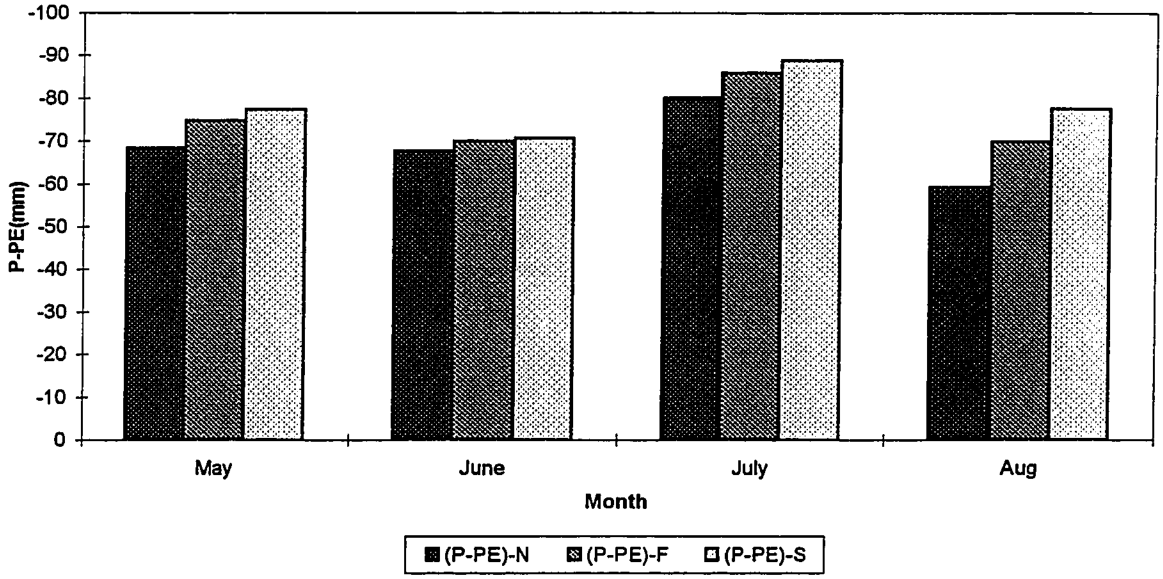


Figure 3.21 P-PE on flat, N and Sfc slopes on the Red Deer River from May to August, 1992 on Two Bar Lake station.

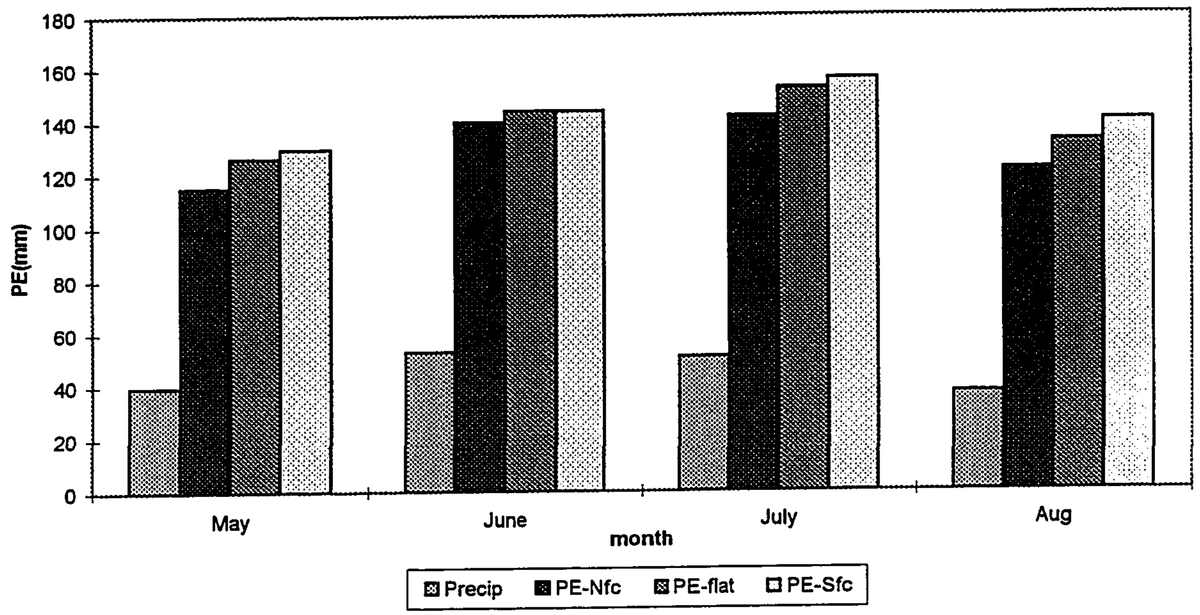


Figure 3.22 PE on flat surface, N and Sfc slopes on the Bow River from May to August, 1992

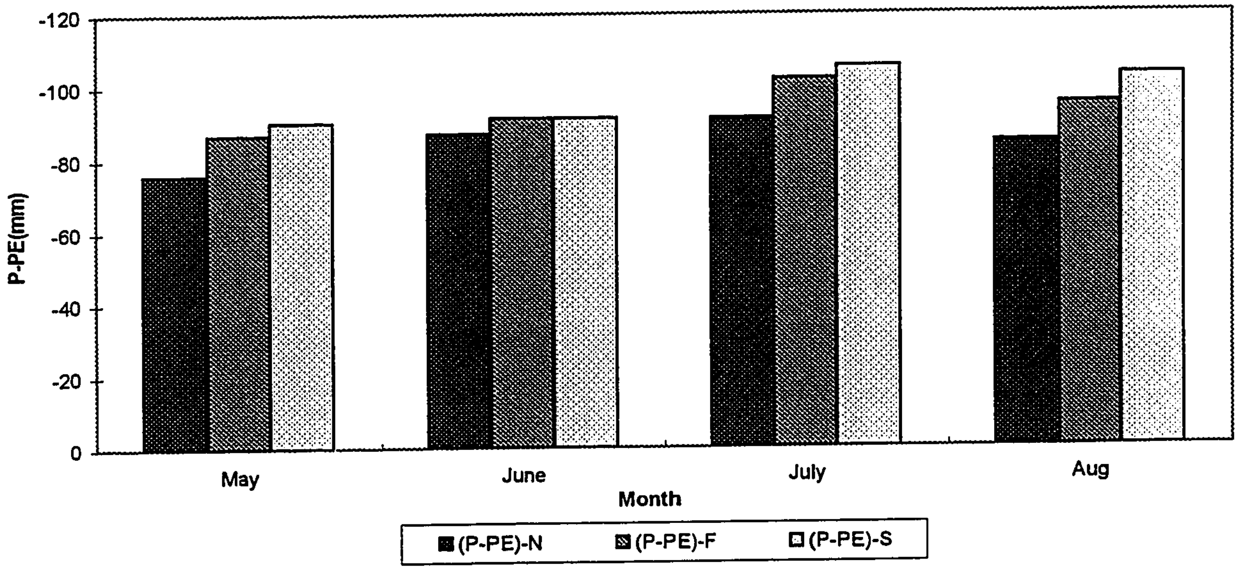


Figure 3.23 P-PE on flat, N and Sfc slopes on the Bow River from May to August , 1992 at the Brooks AHRC.

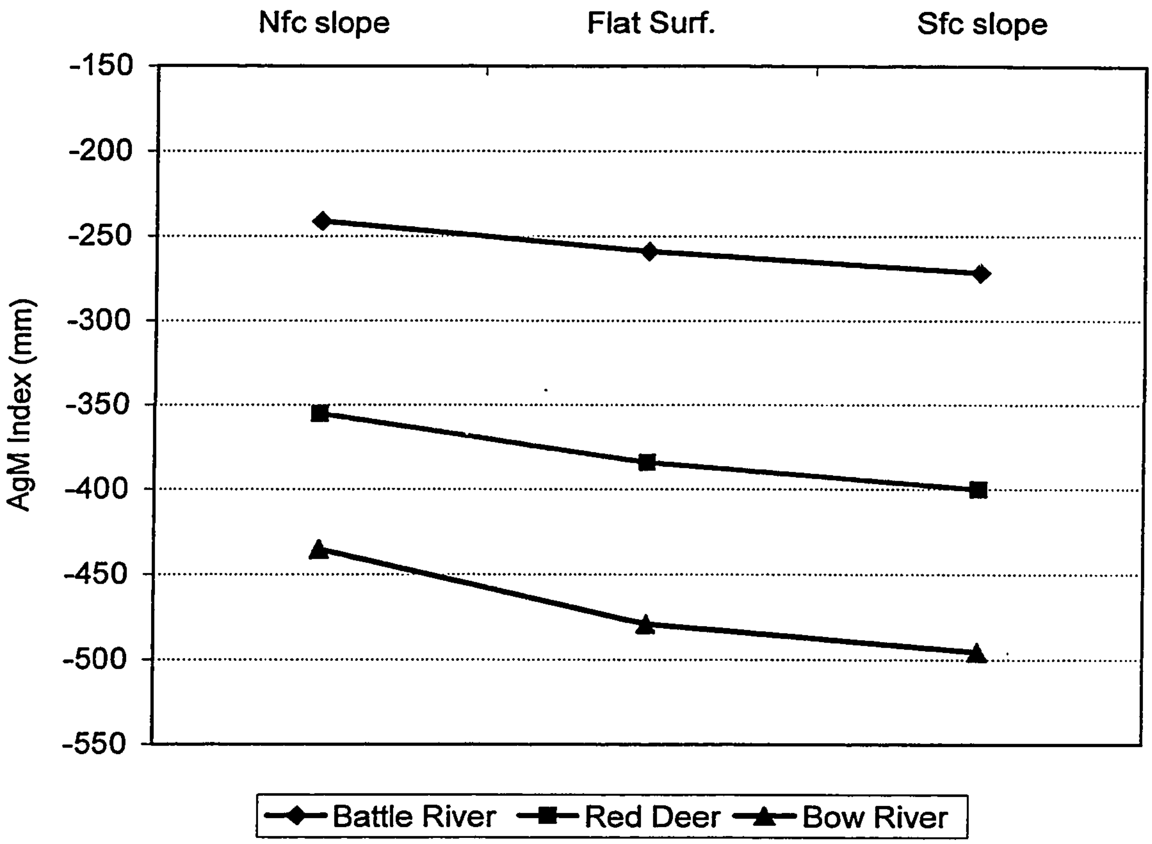


Figure 3.24 Changes of AgM Indices on flat surface, N- and Sfc slopes on the Battle, Red Deer and Bow Rivers.

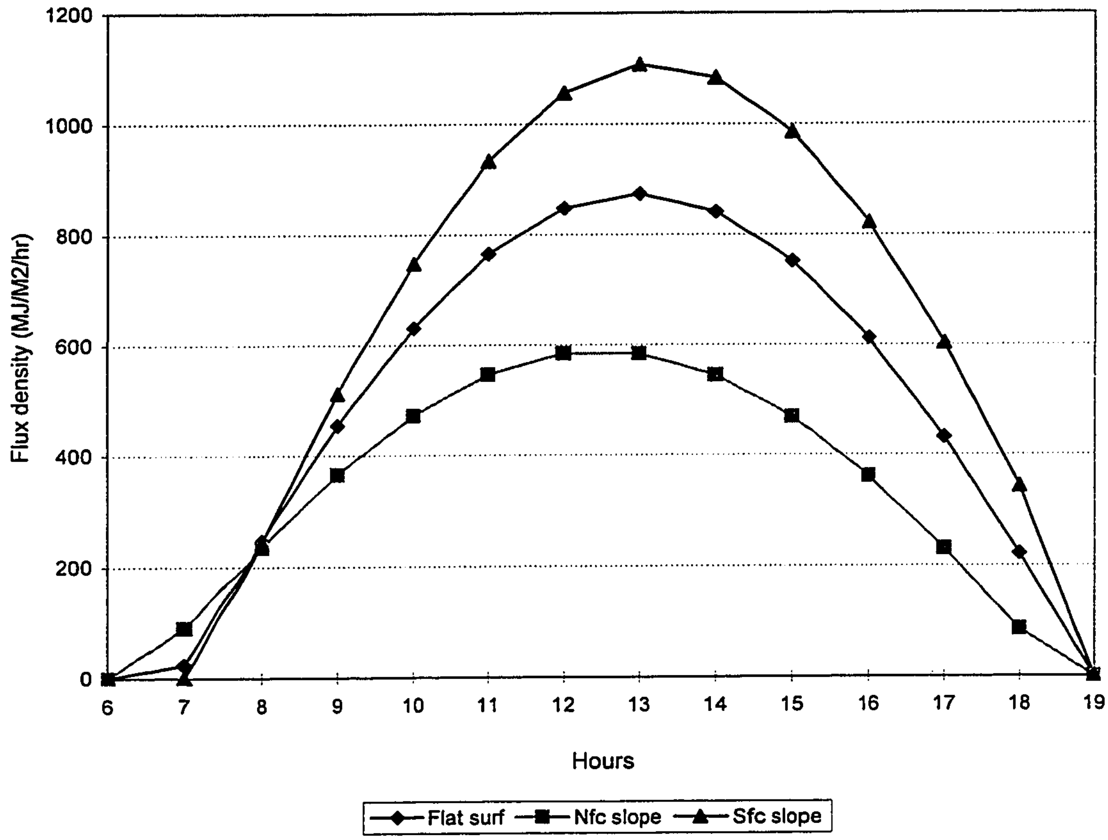


Figure 3.25 Direct short wave radiation on flat surface, N and Sfc slopes on the Bow River on Sept. 21, 1992.

Chapter 4

Slope Angle Measurements and Tree Cover Mapping

4.1 Introduction

Slope angles were measured (Section 4.4) along three river sections on the Battle River, Red Deer River and Bow Rivers to analyze the differences of the angles from one river to another and from Nfc to Sfc slopes in the Bearpaw Formation. In order to reveal the interactions among slope, climate and river erosion at a section on a specific river, the measurements were classified into abandoned slopes, steep active slopes on the outside of river meanders and the slopes intermediate between these two conditions.

The types and rates of slope processes can be quite different on N- and Sfc slopes due to difference of moisture conditions. Churchill's (1981) study in South Dakota showed that mass wasting, principally by many small falls and dry flows, was almost exclusively on Sfc slopes; these falls and dry flows were initiated by desiccation that occurred following precipitation events. In the study area, terraces are found exclusively on the Nfc slope study area on the Red Deer River. They may be a good indication of different erosion rates occurring on N- and Sfc slopes with relatively higher rates on Sfc slope and lower rates on the Nfc (Appendix B).

Moisture differences on differently facing slopes can be significantly reflected by the differences of vegetation in the study area. A good example is the classification of the Ecoregions of Alberta (Strong and Leggat, 1992), in which, vegetation type was used as one of the important factors used to classify ecoregions in Alberta.

Tree mapping in the section of the Battle River and in the three river sections has been carried out to reveal these differences. Besides soil moisture, however, the establishment of trees is controlled by soil type and other climatic factors as well. Climate or microclimate controls the differences of vegetation on the N- and Sfc slopes along the same river or different rivers in the same geological formation. This analysis, instead of directly measuring soil moisture, which is complicated and difficult on slopes, measures tree coverage and slope angles to describe the complexity of antecedent moisture conditions, and the accumulated effect of the present soil moisture conditions (Reid, 1973).

Chapter 4.2 covers tree mapping on the N- and Sfc slopes on the Battle River, the only river valley in the study area regarded as a tree-covered area according to the Alberta Forestry, Lands and Wildlife (1991) standard. In this chapter, tree species and the variation of their physical properties with the variation of slope aspect are also discussed individually. Vegetation on the valley sides of the Red Deer River is also investigated in Chapter 4.3, and the vegetation on the valley sides of the Bow River is briefly mentioned. Chapter 4.4, 4.5 and 4.6 focus on slope angle measurements on the N- and Sfc slopes on the Battle River and Red Deer River as well as on the right and left sides of the Bow River. The difference of slope angles on the banks of the three river are further analyzed in the corresponding subchapters.

4.2 Tree cover mapping on the valley sides of the Battle River

4.2.1 Predominant tree species on the valley sides of the Battle River

Field investigation of tree cover has shown that the tree cover on N- and Sfc slopes of the Battle River is the highest among the three rivers studied. The cover on both the N- and Sfc slopes of the Battle River in the study area increases downstream. The increase on the Sfc slope is more obvious than on the Nfc slope because the cover on the Nfc slope is uniformly higher than that on Sfc slope.

A tree sampling profile across the Battle River between 8—10 km (see Appendix A) was used to investigate predominant species and their physical differences on N- and Sfc slopes. The profile was chosen because the aspects of N- and Sfc slopes in this profile are almost true north and south. Therefore, the differences of characteristics of the vegetation could be the maximized. Predominant tree species and their maximum average heights, diameters and percentage covers of the species are recorded in Table 4.1. The diameters are the averages of ten measurements of each tree species at about 1.5 m above the root stems of the trees and the heights were estimated by using trigonometry.

Table 4.1 Major species on the N- and Sfc slopes in the belt quadrant on the Battle River

Slope	Predominant species	Average Height (m)	Average Diameter (cm)	Cover (%)
Nfc	White spruce*(Picea glauca)*	16	40	32
	Trembling aspen (*Populus tremuloides*)	10	43	57
Sfc	Trembling aspen(*Populus tremuloides*)	6	15	25
	Choke cherry (*Prunus virginana*)	4	10	10
	Beaked willow (*Salix bebbiana*)*			3

*--Beaked willow is a small tree or tall shrub, it is listed here as tree species because of its physical size, and it usually grows on sand bars or relatively wet areas (Johnson, et al., 1995). It may be caused by the disturbance of road construction since the sampling site is close to a road.

The percentage coverage in Table 4.1 on N- and Sfc slopes appears higher than the measurements on the airphotos (Table 4.2) because the measurements on the airphoto do not include steep scarps of the slopes, but the profile does. Few predominant tree species occur on the N- and Sfc slopes. A difference of tree species between N- and Sfc slopes is that there are no white spruce on the Sfc

Table 4.2 Percentage of tree cover in the section of the Battle River mapped on airphotos (Appendix A).

Position of measurement (km)	Nfc (%)	Sfc(%)
0—1	40	5
1—2	45	5
2—3	50	1
3—4	60	2
4—5	55	5
5—6	50	10
6—7	55	10
7—8	70	20
8—9	85	20
9—10	60	25
10—11	50	35
11—12	50	30
12—13	60	35
13—14	70	35
14—15	50	30
15—16	55	10
16—17	60	35
17—18	65	40
18—19	70	45
19—20	70	40
20—21	80	40
21—22	85	45
22—23	85	50
23—24	85	55
24—25	80	55

*--The measurements 19 and 20 on Nfc slope are estimated on the basis of adjacent measurements since the slope was cleared and now is a crop-field.

**-- The No. of measurement corresponds to the measurement number of landlslide incidence along the Battle River.

slope. In terms of physical characteristics, the average heights and the diameters of the species on the Nfc slopes are more than double those of the same species on the Sfc slopes. These differences are good indications of potential moisture differences between N- and Sfc slopes.

Following the change of slope aspects down the river, vegetation on both N- and Sfc slopes changes as well. From km 8—9 to the base of the Bearpaw Formation, the Nfc slope gradually changes to the NW direction and Sfc changes to the SE direction from their former N- and S- directions. The gradual change of slope aspects accompanies changes of tree diameters, heights, and species composition over a short distance. The spruce on the Nfc slope changes from 32% at km 8—9 to almost none downstream except a few close to the bottom of the river valley. The tree diameter and height on the Sfc slope decrease to about 10cm in diameter, and 7-8m in height, individually. These changes indicate that the physical properties of the tree species are sensitive to the change of slope aspects. Considering that the changes of the physical properties of the trees on N- and Sfc slopes gradually follow the change of slope aspects, it is reasonable to observe that the changes are controlled by moisture conditions within the slopes because the soils on both N- and Sfc slopes are similar.

4.2.2 Tree cover mapping on N- and Sfc slopes of the Battle River valley

The differences in species and their physical stature show an overall picture of the vegetation characteristics on the N- and Sfc slopes. Field work and airphoto studies have revealed that tree covers on N- and Sfc slopes have considerable differences along the Battle River. In order to evaluate this difference, Nesby's Vegetation Cover Comparator (1997) was employed to estimate tree cover on slopes from airphotos under stereoscopic view. The comparator gives a set of standard coverage diagrams for mapping tree covers from the airphotos. The scale of the airphotos used for this mapping is 1:30,000 and the length and width of each area for each estimate is 1 km along the main river channel and its corresponding slope length. The estimation started at the same place as the measurement of landslide incidence, and there are two vegetation measurements for each measurement of landslide incidence. The relatively steep scarps (top section) on both N- and Sfc slopes have tree cover of 80-100%, which is higher than the cover below the scarps. Due to this fact, the tree covers below the scarps are mapped for simplicity and ease since the top sections in the tree mapping does not contribute much to the differences of tree cover on both the N- and Sfc slopes. The mapped results are presented in Table 4.2 and the airphotos used for the mapping are summarized in Table 3.2.

The mapped results of tree covers on N- and Sfc slopes on the Battle River in the study area are shown in Figure 4.1. Figure 4.1 shows that some observations on both N- and Sfc slopes are very different. The causes of those abnormal values are either slope aspects or tributary systems, which are indicated by airphotos and 1:20,000 base maps (NTS: R73D05SE). The measured tree covers from measurement 8 to 11 in Figure 4.1 have quite large fluctuations on both N- and Sfc slopes. This reflects changes of slope aspect. There is an unusually low value at 16 in comparison with adjacent measurements. The abnormally low value is caused by a large tributary cutting across the Sfc slope. The relatively low values in measurements 11 and 12 on the Nfc slope have the same cause.

Patches of cropland dotted the section from measurements 19 to 21 in Figure 4.1 on the N- facing slope, where the cover values are estimated in reference to their adjacent natural coverage. Agricultural activities are limited to the Nfc slope in study area, which also is an indication of relatively higher moisture conditions suitable for agriculture on Nfc slopes on the Battle River. The only section where tree cover is less than 6% is near the beginning of the observations on the Sfc slope. This section can be considered non-forested land according to Alberta Vegetation Inventory Standards Manual (1991). If the tree cover on the scarp of the section is considered, it still is classified as forestland.

Statistical analysis reveals (Table 4.3) that the percentage tree covers on Nfc slopes are significantly higher (64.4%) than on the Sfc slopes (27.3%). The percent coverage on the Nfc slope is more than double the coverage on the Sfc slope. This considerable difference of the tree cover reflects the moisture difference on N- and Sfc slopes, and also indicates how strong the effect of slope aspect on soil moisture condition is on sloping surfaces, even on surfaces with an average slope angle of only 6.4°.

4.3 Vegetation along the Red Deer River and Bow River valleys

Tree and shrub patches are found on the Nfc slope on the valley sides of the Red Deer River, especially in measurements 54, 56 and 58 on the Nfc slope, where trees can be as tall as 15 m, but there are almost none on the Sfc slopes. One specific tree-favored location is in back-tilted gullies below main scarps of rotational landslides (measurements 54, 56 and 58). Gullies tends to concentrate precipitation either by snow accumulation or from rainfall. The trees established in some places in this way on the slopes of the Red Deer River in the study area indicate that there is a positive relationship between tree establishment and landslides. This can be explained by the fact that after landsliding, colluvial material is ideal for vegetation to grow under favourable moisture conditions if the material is relatively stable for a period of time. While this vegetation can reduce further slope erosion and increase slope stability (Skempton and Delory, 1957),

Table 4.3 ANOVA of tree cover on N- and Sfc slopes on the Battle River in the mapped section in the Bearpaw Formation.

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Nfc (%)	25	1585	63.4	193.2
Sfc (%)	25	683	27.3	301.9

ANOVA

Source of Variation	*SS*	*D.F.*	*MS*	*F*	*P-value*	*F crit*
Between Groups	16272.1	1.0	16272.1	65.7	0.0	4.0
Within Groups	11881.4	48.0	247.5			
Total	28153.5	49.0				

no effect is expected on deep-seated landslides (Zaruba and Mencl, 1982, p. 175) such as the landslides in the study area.

Since most of the Sfc slopes on the Red Deer River are sparsely vegetated and the vegetation cover on the Nfc slope is not continuous, it is unnecessary to map the vegetation cover on the N- and Sfc slopes on the Red Deer River. The predominant species are tall shrubs and low trees. The species coverage is much lower than that on the Battle River since the area on the Red Deer River is within the Mixed Grassland Ecoregion (Strong and Leggat, 1992). Plants appear in patches mostly on the Nfc slope throughout the section of the Red Deer River, and occasionally patches of vegetation in a few small gullies appear on both valley sides of the Red Deer River in the middle portion of this study section. Even so, within the gullies, there is still predominantly higher coverage on Nfc slopes than on the Sfc slopes. Field investigation shows the following species in Table 4.4 are commonly found on Nfc slopes (sampled from km 16 to 18 in Appendix B).

No trees were found on the sides of the Bow River in the study area, but there are still small patches of shrubs on the Nfc slopes in the section of the Bow River mapped. Further investigation is not justified because the coverage is very low since the section is in the Dry Mixed Grass Ecoregion (Strong and Leggat, 1992), and also the slope angles are steeper than the angles of the Red Deer and

Table 4.4 Common plant species on the Nfc slope of the Red Deer River.

Trembling aspen (*Populus tremuloides*)
Black cottonwood (*Populus trichocarpa*)
Silver-berry (*Elaeagnus commutata*),
Saskatoon-berry (*Amelanchier alnifolia*),
Canada buffaloberry (*Shepherdia canadensis*),
Twining honeysuckle (*Lonicera dioice var. Glaucessens*),
Thorny buffaloberry (*Shepherdia Argentea*),--tall shrubs or small trees
Ground juniper (*Juniperus communis*),
Creeping juniper (*Juniperus horizontalis*),
Water birch (*Betula occidentalis*),
Sandbar willow (*Salix oxigua*).

Battle River valleys. Drier climate and steeper slopes on the Bow River limit vegetation establishment on the sides of the Bow River, even on the N- facing slope.

4.4 Slope angle measurements

Since the river valleys are postglacial in origin (Chapter 3), they reflect the effects of morphological processes resulting from the interaction between climates, slopes and channels (Sauchyn, 1993). Different rates and types of slope processes result in different slope angles and slope profiles (Churchill, 1981). When the processes involve direct removal of material from a slope, they tend to cause parallel retreat of the rest, and the slope is weathering-limited (Selby, 1993). When the toes of slope are continuously being eroded by a river, the slopes tend to be active and steep. Slopes abandoned by basal river erosion are very different from those slopes that are undergoing active erosion by rivers. On an abandoned slope, erosion of higher elevations and accumulation of colluvium at lower elevations of the slope dominate. These processes involve downslope soil transportation, tending to cause slope flatening, and the slope is classified as transport-limited (Selby, 1993). The accumulation and the removal of the accumulation by rivers may govern slope angles at the lower portion of the slope profile. If accumulation is greater than the removal, the slope angle is usually lower than where accumulation is less than removal.

This study investigates slope angles by measuring them from 1:20,000 base maps supplemented by airphotos. The contour interval of the maps is 10 m. At least, one interval was used for every measurement, and there was no interpolation of contours during the measurement of vertical distances. That means the vertical distance for every measurement is at least 10 m or higher. The measurements were checked by a hand-held clinometer in the field, and no inconsistencies were found.

Measurements were carried out systematically following the river directions and slopes were classified into two types, active slopes and abandoned slopes. The abandoned slopes can have scarps below which the section of slope is uniform, gentle and covered by colluvial materials. Active slopes are undercut by current rivers, and their surfaces are straight and relatively steep. For this type of slope, the entire slope profiles were measured. For abandoned slopes, if the entire slopes were straight and had no scarps, whole slopes were measured; if there were scarps, slopes in the accumulation zones were measured since they had relatively regular and low gradient slope profiles.

Several rules were used to guide these measurements in order to systematically analyze various factors that affect different slope angles. The distance from one measurement to the next on the same slope is 400 m along the main river channel, which is used as a reference distance line to make systematic measurements on both sides of a river. Measurements do not include terraces, tributary gullies and the main scarps on slopes caused by landslides. The depletion zones (Cruden and Varnes, 1996), where they are obvious and still recognizable on both maps and airphotos, are excluded from the measurements because their main scarps are steep. Slopes in the accumulation zones of landslides were measured if the distinctive landslide features are still obvious.

For the abandoned slopes, sometimes it was difficult to locate which contour line should be considered as a break to separate the slope from fluvial deposits whose surfaces are gently sloped. This condition occurs where the change in distance between adjacent contour lines down slope is gradual. For this case, airphotos were used to help locate the slope break. At times, this method may not be accurate, but fortunately, the abandoned slopes usually have straight and uniform surfaces, and the entire slopes were measured to reduce errors.

The precision of the measurements varies depending on how many contour intervals are used for a specific measurement. Every reading was estimated to within 0.3 mm during the measurement. However, the more contour intervals used, the higher the precision since the scale of the maps is fixed. Based on the map scale, interval distance, and the estimated reading, if a slope angle measured is 10^0, and a minimum of one contour pair is used, the error could be as large as ±9%. That means if the slope angle is about 10^0, the error could be 0.9^0.

Fortunately, few measurements were made by using one interval along the Red Deer River and the Bow River, and none was made along the Battle River. If two contour intervals are used on a 10° slope, the error is only about 1.7%. The 9% error would rarely be the case since, if the slope angles are steeper than 10^0, they are mostly active and being actively eroded by the river current, the surfaces are uniform and straight, and more contour intervals are readily available. Even if half the measurements were done by using one interval, and the other half were made by using two intervals, the errors, at most, would be 5.4%, which is still acceptable for slope angle measurements from maps. Since the methods used in slope measurements are systematic, the actual errors are likely to be much less than the maximum error described above.

Measurements of slopes, either active or abandoned, are used to explain the mechanisms of the formation of the slope systems in different climatic zones. These are supposed to be controlled by the interaction between climate and slope itself if its material and geologic history are the same. The differences in slope forms are the result of the variable operation of geomorphological processes which, in turn, have been controlled by the non-uniform distribution of precipitation and direct insolation (Kennedy, 1976). Even for the steep active slopes undercut by river currents, the steepness of the slope angles may differ from one river to another because of different moisture conditions in the study area, even if the materials involved are the same or similar.

For abandoned slopes whose surfaces are uniform, low gradient, and covered by colluvial material, the mechanism of the formation of the slopes is as follows. First, deep-seated rotational landslides reduce steep slopes to more gentle slopes; then successive, small, rotational landslides occur to further flatten the slope to lower slope angles; subsequently, slope wash dominates to make the slopes uniform at so-called ultimate slope angles. This model of slope formation was first developed by Hutchinson (1967, 1973) in SE England for London Clay and has been widely accepted as Hutchinson's model in soft geologic material.

The abandoned, uniform and flat slopes on the Battle River are well explained by Hutchinson's slope model from SE England. The two locations are in the same Ectropic climatic zone according to Budel's (1982, Figure 13) classification. Koppen's Classification puts the study area in climatic zones *Dbf* and Hutchinson's study area in *Cbf*. Here, *D* is cold boreal forest climate, and *C* is warm temperate climates, and *bf* stands for moist climates with adequate precipitation throughout the year of vegetative growth (*f*) and warm summer, in which the warmest month has a mean temperature below 22° C (*b*). The difference between the two is only the mean temperature, and moisture conditions are the same (*bf*). So Hutchinson's model might reasonably apply.

There are many slope models, either conceptual or mathematical, to explain slope profiles in different regions under different climates (Hutchinson, 1967; Carson, 1976; Chandler, 1982; Francis, 1987). Hutchinson's (1967) model is used to explain the slope pattern on the Battle River based on the abandoned slope profiles in the study area. In addition to the above reasons, the colluvial material has an average angle of 6.4°, within the range of residual friction angles of montmorillonitic shale (Watry and Ehlig, 1995). Other models can explain the slope profiles in arid areas, such as those along the Red Deer River and Bow River. Which slope profiles on the three river sections can be explained by which slope models in the study area is to be answered by the following measurements of slope angles on the sides of the three river sections.

4.4.1 Slope angles along the Battle River

Slope angles on the N- and Sfc slopes in the mapped section of the Battle River were measured below steep scarps (see the airphotos in Table 3.2) in a total of 36 paired measurements made on base maps of 1:20,000 (NTS: R73D05SE). The measurements cover the section from measurement 14 to 24 km on the airphoto overlays in the Appendix A. The entire dataset is listed in Table 4.5, which shows a slope profile with a narrow range of variation between 4.5 to 10 degrees (Figure 4.2). The measurements give an average slope angle of 6.4° which is slightly lower than the average angle of the abandoned slopes in the

Table 4.5 Slope angles (°) on N- and Sfc and Sfc slopes on the Battle River.

No.	Nfc-Angle	Sfc-Angle
1	4.3	4.9
2	7.8	4.3
3	5.7	5.4
4	5.7	4.3
5	6.0	5.4
6	5.7	6.1
7	7.1	5.9
8	6.6	4.9
9	6.3	4.1
10	6.3	4.3
11	5.9	5.7
12	6.8	8.5
13	5.7	5.7
14	5.7	6.0
15	6.8	6.2
16	7.1	6.2
17	5.7	6.9
18	6.5	7.4
19	6.2	7.6
20	10.0	6.6
21	8.5	6.6
22	7.8	6.6
23	8.7	7.1
24	7.4	5.4
25	5.2	9.5
26	7.5	5.5
27	9.0	8.5
28	6.6	7.6
29	8.1	8.1
30	9.5	8.5
31	5.7	8.7
32	3.9	5.0
33	4.5	4.2
34	5.9	5.5
35	4.1	6.6
36	6.2	7.1
Average	**6.6**	**6.3**

* The interval of the measurements is 400 m. The measurements were made from 14 to 24 km on the airphoto overlays in Appendix A.

London clay (8°) in Hutchinson's (1967) study. More importantly, the angle is close to the residual friction angle of bentonitic shale (φ_r) (Watry and Ehlig, 1995) and could represent the angle of repose of dry bentonic shale. However, the angle also lies within a range of threshold slope angles of 6-14° for soils from weathered clays and shales in the semi-frictional condition with the possibility of high water-table (Selby, 1993, p.362). Slopes abandoned by the modern Battle River are covered by colluvium below scarps on both N- and Sfc slopes.

The slope angles on the N- and Sfc slopes in Table 4.6 show no statistical difference. The overall average slope angle on the Nfc slope (6.6°) is almost the same as the Sfc slope (6.3°). Other studies (Kennedy, 1976; Churchill, 1981) in arid or semi-arid areas indicate that the Nfc slopes should have lower angles than Sfc slopes.

To consider the slope profile controlled by stratigraphy (the same on both N- and Sfc slopes), the changes of slope aspect, orientation, and the height of caprock (sandstone unit) in the section where slope angles were measured, the dataset is divided into two subsets. The first 24 measurements (upstream) on both slopes, whose orientations are northwest or southeast, are in the section of thicker caprock than that in the last 12 measurements. The average slope angle of the first 24 measurements on Nfc slope is 6.7°, and the angle on Sfc slope is 4.9° (Table 4.7). It turns out that the average slope angle on Nfc slopes is steeper than on Sfc

Table 4.6 ANOVA of slope angles (°) on N- and Sfc slopes on the Battle River.

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Nfc slopes	36	236.6	6.6	2.1
Sfc slope	36	226.9	6.3	2.1

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F-value*	*P-value*	*F crit*
Between Groups	1.3	1.0	1.3	0.63	0.43	3.98
Within Groups	146.6	70.0	2.1			
Total	147.9	71.0				

Table 4.7 ANOVA of slope angles (°) of first 24 measurements on N- and Sfc slopes on the Battle River in the section where caprock exists.

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Nfc slope	24	160.5	6.7	1.5
Sfc slope	24	141.9	5.9	1.3

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F-value*	*P-value*	*F crit*
Between Groups	7.2	1.0	7.2	5.080	0.029	4.052
Within Groups	65.3	46.0	1.4			
Total	72.5	47.0				

slopes and the difference is statistically significant based on the test of ANOVA (Table 4.7).

The second sub-dataset includes 12 pairs of measurements with the orientation of southwest to northeast. The two datasets are incidentally separated at a big meander of the Battle River. The caprock in this section is very thin and its effects diminish down stream. This change of stratigraphy resulted in more uniform slope surfaces, and the slope profile appears to be explained by Hutchinson's (1967, 1973) slope model. The average slope angle on Nfc slope is 6.3^0, which is lower than that in the first section, but the angle on Sfc slopes steepens, and averages 7.1^0. However, the difference between Nfc and Sfc slopes is not statistically significant. The slope angle is supposed to be the ultimate slope angle at which the hillslope is stable against landsliding, and is equal to the angle of internal friction of the material (Selby, 1993, p.362).

4.4.2 Interpretation of the slope angles along the Battle River

Average slope angles on Nfc slopes in the first section are greater than on Sfc slopes, which may appear to contradict other studies as discussed in the introduction (asymmetrical slopes) that the Nfc slopes should be gentler than Sfc slopes. Considering other factors on the Sfc slopes, such as the vegetation coverage discussed in the first part of this chapter, the Sfc slopes have much lower tree coverage and higher bare ground than on the Nfc slopes (Figure 4.1). On abandoned slopes, these differences could result in higher rates of erosion and surface runoff on the Sfc slopes because the tree cover protects against this type of erosion on the Nfc slopes. Higher tree cover should reduce erosion and weathering processes. There is almost no discharge of the eroded debris since the base of the Battle River valley has been abandoned. This process could cause the flattening of Sfc slope surfaces to be faster than the densely tree-covered Nfc slopes.

The average slope angle on Sfc slopes in the second section (last 12 measurements) shows no significant difference from the average Nfc slope angle. This may be explained by the change of slope aspects in this section and the denser tree covers on both N- and Sfc slopes, in addition to the small number of measurements. The average slope angle on Nfc slopes in the second section appears to be the same as in the first section, but the slope angles on the Sfc slopes have a relatively big increase, from 5.9 to 7.1°, from the first section to the second (Tables 4.7 and 4.8).

The average slope profile along the Battle River suggests that the slope system on the Battle River can be explained by Hutchinson's (1967) model based

Table 4.8 ANOVA of slope angles (°) of the last 12 measurements on N- and Sfc slopes on the Battle River in the section where caprock exists.

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Nfc slope	12	76.1	6.3	3.4
Sfc slope	12	85.0	7.1	2.9

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F-value*	*P-value*	*F crit*
Between Groups	3.3	1	3.3	1.04	0.32	4.30
Within Groups	69.4	22	3.2			
Total	72.7	23				

on the overall slope angle, material, the state of the abandonment of the slopes, and the climate in the section.

4.5 Slope angles along the Red Deer River

Slope angles along the Red Deer valley were measured from R82P01NE (NTS) at 1:20, 000. The measurements cover the section from measurement 28 to 42 km on the airphoto overlays in the Appendix B. Slope profiles in the Red Deer valley differ from those along the Battle River in terms of the range and steepness of slope angles, and the role of the river. Two distinctive profiles appear in the Red Deer valley; one is active and steep (32-38°) with short slope profiles eroded by the modern river on the outside of the river meanders, the other is low gradient (4-6°), long abandoned by the river, with colluvial accumulation on the lower portion of the profile. These two valley profile types are common along both the Red Deer and Bow River valleys.

The same methods were used to measure the slope angles on the Battle River as were applied to the Red Deer River. Slope angles are listed in Table 4.9. The overall measurements give a good representation of slope status, either active or abandoned, following the variation of the slope angles (Figure 4.3) corresponding to the variation of river sinuosity. Higher slope angles on either

Table 4.9 Measured slope angles on N- and Sfc slopes (°) on the Red Deer River.

No.	Nfc-Angle	Sfc-Angle
1	13.0*	32.0*
2	18.4*	12.5*
3	31.0*	4.6
4	26.6*	4.4
5	38.7*	6.7
6	11.3*	5.7
7	7.1	9.0
8	5.0	26.6*
9	4.6	29.7*
10	4.8	8.5
11	9.5	8.1
12	12.5*	4.1
13	6.3	5.4
14	6.7	7.8
15	5.7	7.9
16	4.1	7.1
17	8.7	7.4
18	6.3	4.6
19	7.9	5.4
20	26.6*	5.0
21	21.8*	5.2
22	12.1*	4.4
23	15.9*	6.0
24	9.5	4.8
25	12.5*	5.0
26	5.2	4.4
27	5.4	4.4
28	7.1	4.4
29	4.6	7.1
30	5.7	4.8
31	4.1	4.4
32	5.4	6.8
33	6.7	6.8
34	7.8	6.2
35	4.1	4.6
36	5.4	5.0
37	10.3*	5.0
38	5.7	7.1
39	11.3*	3.7
Average	**10.7**	**7.8**

*--Measurements are not abandoned slope angles, and the rest are the abandoned slope angles.

*-- Interval of the measurements is 400 m, 100 m interval was used around meanders(11 measurements).

*-- Section measured from 28 to 42 km in Appendix B.

*--Statistical results are listed in Table 4.10.

N- or Sfc slopes result in the lower slope angle on the opposite slopes, and this pattern is demonstrated by raw data in Figure 4.3 and the opposing phases of the polynomial fitted function. To consider the role micro-climate plays to cause different slope processes on N- and Sfc slopes, it is necessary to classify the measurements into steep, active slopes and flat abandoned slopes to single out sections where slope angles are controlled solely by climate and sections where the slope angles are controlled by climate and the flowing river.

Average slope angles on N- and Sfc slopes are 10.7^0 and 7.8^0 respectively (Table 4.10). This underestimates the overall slope angles on the Red Deer because the measurements were made on the lower section of slope where accumulation occurs and the steeper top section was not included in these measurements.

Similar results of the slope angles on the N- and Sfc slopes on the Battle River occur on the Red Deer River. The slope angle on the Nfc slope is greater than the Sfc slope; however, the difference is not statistically significant. The same explanations used in Chapter 4.4.2 can be applied here as well. Measurements were not made on the whole slope profile (except on active slopes) but on the lower section of the slopes covered by colluvium. Since the height of the slopes in the Red Deer valley is substantial (see Chapter 3), there is enough area to generate colluvial material under the dry climatic conditions (Dry Mixed

Table 4.10 ANOVA of slope angle (°) on the Red Deer River for the entire data set.

ANOVA: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Nfc slope	39	415.5	10.7	65.8
Sfc slope	39	302.8	7.8	43.6

ANOVA

Source of Variation	SS	Df	MS	F	P-value	F crit
Between Groups	162.9	1	162.9	3.0	0.1	4.0
Within Groups	4157.8	76	54.7			
Total	4320.8	77				

Grassland in Strong and Leggat's (1992) classification), especially on the Sfc slope. This results in a considerable amount of colluvial accumulation brought down to the lower section from above. The production of the colluvial material on the Nfc slope may be less than the Sfc slope because the Sfc slope is drier and has less vegetation cover, which in turn generates the higher rate of surficial erosion on the Sfc slopes compared to the Nfc slopes. As a consequence, the lower section of the Sfc slope would receive more accumulation of colluvium than on the Nfc slope, and the discharge of the material from the modern Red Deer River may be less than the accumulation of the material. This is reflected very well on the airphotos as well as from the field investigation.

The average slope angles on the N- and Sfc slopes are strongly affected by the active, steeper slope angles on both N- and Sfc slopes. Statistical analysis (Table 4.10) of the difference of the slope angles on the N- and Sfc slopes indicates that the difference is not significant because of the high variance, even though the difference between N- and Sfc slopes is 2.9°. The measurements were broken into two groups to analyze the statistical significance of the difference of the slope angles on N- and Sfc slopes. The results show that the average slope angles on the N- and Sfc slopes from the first half of the dataset (first 19) are 12.0° and 10.4° individually, but the difference is still not significant (Table 4.11). However, the difference on the second half shows the significant difference (Table

Table 4.11 Test of the difference of slope angles (°) of the first 19 measurements on N- and Sfc slopes on Red Deer River

ANOVA: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Nfc slope	19	228.3	12.0	96.3
Sfc slope	19	197.5	10.4	76.7

ANOVA

Source of Variation	SS	Df	MS	F	P-value	F crit
Between Groups	24.95	1.0	25.0	0.3	0.6	4.1
Within Groups	3112.97	36.0	86.5			
Total	3137.92	37				

Table 4.12 Test of the difference of slope angles (°) of the last 20 measurements on N- and Sfc slopes on Red Deer River.

ANOVA: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Nfc slope	20	187.3	9.4	36.8
Sfc slope	20	105.3	5.3	1.1

ANOVA

Source of Variation	SS	Df	MS	F	P-value	F crit
Between Groups	167.9	1.0	167.9	8.9	0.0	4.1
Within Groups	720.3	38.0	19.0			
Total	888.1	39.0				

4.12) between the N- and Sfc slopes; the Nfc slope is greater than the Sfc slope, but the steep, active slope angles may play an important role in this analysis.

Steep, active bedrock slopes and the abandoned colluvium-covered slopes are classified to find out if the angles of the abandoned slopes are different from the angles of abandoned slopes on the Battle River, and also to examine if the steep, active slopes on the Red Deer River are different from the active slopes on the Bow River. The classification was carried out using 1:20,000 maps in reference to the airphotos in the section. Table 4.13 shows the statistical results for the abandoned slopes. First, there are different numbers of measurements in the same section with only 25 measurements on the Nfc slope but 35 on the Sfc slope. The difference of the measurements indicates that the Sfc slope has a higher percentage of the abandoned slopes. The differences of abandoned slopes may be caused by higher erosion rates operating on Sfc slopes than on Nfc slopes. This may be explained by Dohrenwend's (1978) study in the semiarid area of central California. That study indicated that higher slope wash erosion on Sfc slopes pushed streams against Nfc slopes. Erosion by these streams steepened the Nfc slopes.

The average abandoned slope angles on the N- and Sfc slopes are 6.1° and 5.8°, and the overall average is about 6.0°, which is very close to the abandoned slope angle on the Battle River (6.4° on average). The result is consistent with that

Table 4.13 ANOVA of abandoned slope angles (°) on the N- and Sfc slopes on the Red Deer River.

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Nfc slope	25	153.5	6.1	2.5
Sfc slope	35	202.0	5.8	2.1

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.0	1	2.01	0.89	0.35	4.01
Within Groups	131.1	58	2.26			
Total	133.2	59				

on the Battle River because colluvial materials are essentially non-cohesive ($c' = 0$) and the maximum angle at which the hillslope is stable against landsliding is equal to the residual friction angle of the soil, φ_r (Selby, 1993, p. 263). The relationship holds true for non-cohesive material whether the slope is dry or submerged provided that there is no lateral seepage of water. The residual friction angle is independent of the thickness of the deposit and its rate of accumulation. The value of φ_r is between 6.7° to 6.9° from tests of remolded samples of bentonite (Watry and Ehlig, 1995).

Eleven more measurements were carried out on the active, steep, bedrock slopes at 100 m intervals following the main river channel between every two measurements in Table 4.9 on the outside of the meanders of the Red Deer River. The average active bedrock slope angles on the meanders are 29.6^0 and 30.2^0 on N- and Sfc slopes individually, and the overall average is about 30^0. The steepest slope angle is 38.7°. The angles on N- and Sfc slopes are not significantly different.

4.6 Slope angles on the right and left sides of the Bow River

Slope profiles in the Bow River valley are similar to the profiles in the Red Deer valley, but the slopes on the Bow are much shorter than the Red Deer, and the vegetation is sparse to none on the both right and left valley sides of the Bow River. The right and left valley sides are used here since three aspects of measurements on right or left sides are not facing north or south because of higher river sinuosity. As defined in Chapter 3, previously, the Nfc slope refers to slope aspects within a range between 90-270° while Sfc facing refers to slope aspects within a range between 270-90° clockwise. Right and left refer to banks viewed downstream.

The measurements made on map sheet (NTS: R82I09SW) are listed in Table 4.14 with their aspects. The measurements cover the section from measurement 22 to 36 km on the airphoto overlays in the Appendix C. The range of slope angles is 4 to 56^0, which reflects not only measurements that include active and inactive slopes, but also indicates a higher variation of slope angles on the right and left sides of the Bow River. The pattern of the variation is the same as in the Red Deer; higher slope angles on one side generally contrast with lower slope angles on the opposite side (Figure 4.4). The average slope angles on the right and left sides of the Bow River are also affected by a few measurements of higher slope angles, as indicated in Table 4.15. The average slope angles on the right valley side and left side are 10.8 and 18.8° individually which are much higher than the average valley side slope angles in the Red Deer and the Battle. The average slope angle on the right valley side is lower than on the left side, and the difference is statistically significant (Table 4.15). This result is different from

Table 4.14 Measurements of slope angles (°) on R- and L-sides, slope angles sorted by aspect along the Bow River.

Rb-Angle	Rb-Aspect	Lb-Angle	Lb-Aspect
18.4	12	26.6	165
24.4	17	17.4	166
25.7	20	6.5*	183
16.9	21	6.5*	187
16.7	25	5.9*	193
20.6	32	3.2*	209
16.1	40	2.7**	209
3.3*	48	2.9**	219
3.4*	55	19.3	223
35.5	55	35.0	230
3.4*	75	3.9*	234
3.3*	76	45.0	238
10.3*	80	21.3	249
2.1	84	12.2	251
3.9*	87	11.6	255
10.6*	87	30.3	260
10.7*	87	21.8	266
2.5	88	8.1*	268
3.1*	90	11.3	274
12.5	93	11.8	275
21.8	94	40.5	280
4.5*	95	56.3	281
10.8	99	16.7	285
9.5*	104	6.5*	286
8.0*	104	17.4	289
3.7*	104	14.8	294
11.0	105	12.1	294
8.2*	106	35.0	295
4.3*	110	29.1	295
4.0*	116	22.6	303
20.6	120	20.6	306
4.6*	121	26.6	308
7.9*	122	20.0	310
5.0*	127	22.4	316
10.6*	130	13.0	319
10.8		**18.8**	

*--Abandoned slope angles. Rb--right side, and Lb--left side.
**--Terrance involved in the measurement.
Statistical results are in table 4.15.
Interval of the measurements is 400 m.
Section measured from 22 to 36 km on the airphoto overlays in the Appendix C.

the slope angles on the N- and Sfc slopes on the Red Deer River. The reason may be that the shorter slopes on the sides of the Bow River have a lower production of colluvial material because of smaller source areas discharging to a unit distance of Bow River. Therefore, there is less accumulation of colluvial material on the lower portion of the slopes and delivered to modern Bow River and fewer abandoned slopes protected by sediment. Thus, the slope angle on right valley side is smaller than the angle on the left side. The overall difference of slope angles on right and left sides is consistent with other studies mentioned in this chapter.

Further analysis was done by sorting out the measurements by slope aspects in increasing order, and then the relationship between slope angles and their aspects was plotted to reveal variations of slope angles with the slope aspects. Trend lines of polynomial functions were employed to display the variation of the slope angles with aspect. Figures 4.5 and 4.6 indicate that the negative correlation of slope angles on right and left sides appear obvious following the increase of slope aspects. This correlation indicates that the higher slope angles on one side result in the lower slope angles on the opposite, and vice versa. The figures also show that the average slope angle on the left side is much higher than for the right side. For the section in the figures where both sides have

Table 4.15 Statistical analysis of slope angles (°) on right or left sides of the Bow River.

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Rb-angle	35	378.0	10.8	65.8
Lb-angle	35	656.4	18.8	162.1

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F-value*	*P-value*	*F crit*
Between Groups	1106.8	1.0	1106.8	9.7	0.0	4.0
Within Groups	7750.0	68.0	114.0			
Total	8856.8	69.0				

low slope angles, the angles on the left side are still much higher than the right side.

The same classification as was used on the Red Deer River was applied to the Bow River as well. First, the abandoned slope angles were sorted out on right and left sides, and then, statistical analysis applied to the data to find out if there is a potential difference of the active slope angles between the Red Deer River and Bow River. The average abandoned slope angle on the right and left sides are 6.1^0 and 5.8^0 individually (Table 4.13), and the angle on the right side is slightly higher than on the left side. The difference is not statistically significant (Table 4.16) as expected, since the overall average is about 6.0^0, which is close to the abandoned slope angles on the Red Deer River and the Battle River as well. As mentioned in this chapter, the angle is apparently independent of climatic differences between the three rivers, and this result again shows a consistency among the three rivers for the abandoned slopes. The measurements of the abandoned slope angles were made on the right and left sides by using the same interval (100 m) as on the Red Deer River following the main river channel within the same section on the Bow River. However, the 20 measurements made on right valley side is much more than the 7 on the left valley side. The numbers of the measurements on right and left sides of the Bow River are just opposite to the numbers on the N- and Sfc slopes on the Red Deer River. This may be explained by a lesser accumulation of colluvial material on the Bow River slopes, and more landslides from the right

Table 4.16 ANOVA of abandoned slope angles on right and left sides on the Bow River.

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Right Side	25	161.4	6.5	11.6
Left Side	13	93.0	7.2	12.7

ANOVA

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4.1	1	4.14	0.35	0.56	4.11
Within Groups	430.1	36	11.95			
Total	434.3	37				

valley side may generate more colluvial material to push the river towards the opposite side and cause more abandoned slopes on the right side than on the left side.

Active, steep slope angles on the outside meanders were sorted out from Table 4.14. The averages of the active slope angles on the right and left sides are 27.3° and 43.0°, respectively, based on 18 measurements on the right valley side and 13 measurements on the left side (unmarked in Table 4.14). The large difference between left and right slopes may be caused by the factor that the measurements were carried out only for one third of the section (from 22 to 36 km on the airphoto overlays in the Appendix C) along the Bow River in the study area. The overall average of the active slope angle on the Bow River is 35.1°, which is significantly higher than the angle on the Red Deer River (30°). The steepest active slope angle is 51.3°, which is about 20 degrees higher than the steepest angle on the Red Deer River. The difference of the active slope angles on right and left sides is statistically significant.

4.7 Discussion

Chapter 2 has clearly established the significantly greater landslide incidence on Nfc slopes than on Sfc slopes in the sections of the Red Deer River and Bow River. It is evident that the difference of slope aspect is obviously the reason for the difference of landslide incidence, which was atributed to aspect-induced variations in topoclimatic factors, particularly moisture budget (Churchill, 1981). The difference of slope aspect determines the intensity of solar radiation that slopes with different aspects receive and of course determines the difference of temperatures as well (Wilson, 1970; Ueno, et al., 1989; Varley, et al., 1996). Over the course of a year, Sfc slopes receive roughly four times more direct solar radiation than Nfc slopes from 0 to 60 degrees north latitude (Buffo, et al., 1972). As a consequence, the Sfc slopes are not only drier in general but are subject to more frequent and intense episodes of wetting and drying (Churchill, 1981). Slope insolation provides a basis for the differentiation of micro-environments, within which various soil moisture regimes control differences in soil behaviour (Reid, 1973). Differential process activity, in turn, can be explained by aspect-induced variations in topoclimatic factors, particularly moisture budget. For example, hillslopes in arid areas tend to be shorter, steeper, and have smaller radii of curvature of the convex segment than those in humid areas (Churchill, 1981).

Because of more rapid and intense desiccation, Sfc slopes will generally have lower antecedent moisture levels at the outset of any given precipitation event relative to their Nfc counterparts (Reid, 1973; Churchill, 1981). Therefore, Nfc slopes retain higher moisture levels over longer periods of time, and sustained higher moisture levels also result in deeper penetration of the wetting front. Because Nfc slopes have lower internal cohesion (due to higher moisture regime) than the indurated bedrock, the slopes are more susceptible to landslides.

Since soil moisture is of importance to many slope processes, any spatial variability induced through land aspect suggests present-day rates of developing slope asymmetry may be developing at present (Churchill, 1981). It is well known that increased moisture is one of the key factors affecting slope stabilities by decreasing effective stress (Brunsden, 1984; Selby, 1993). Landslide incidence can significantly differ between N- and Sfc slopes due to the long term, accumulated effect of moisture difference (Reid, 1973). The different modes of landsliding can directly yield different slope angles as indicated by asymmetrical slope profiles. These can be used as a good indication of the differences in slope processes in moisture-deficient regions as other studies have shown (Gilbert and Wolfe, 1959; Churchill, 1981). The smaller inclination of Nfc slopes results both from the tendency of landslides to operate toward increased slope stability and the greater role assumed by wash and rilling (Churchill, 1981).

Moisture conditions partially control the vegetation distribution, density and species, which have been defined as ecoclimate (AgMet Rating Group, 1985;

Alberta Soils Advisory Committee, 1987). In an ecoregion, the relationship between climate and vegetation is formally defined as "an area characterized by distinctive regional climate as expressed by vegetation" (Subcommittee on Biophysical Land Classification, 1969). Moisture conditions, expressed by Climatic Moisture Balance (mm) and Agro-Climatic Moisture Index, are one of the key factors in determining each ecoregion (Strong and Leggat, 1992). Churchill's (1981) study in the badlands of South Dakota revealed that the limited vegetation is entirely restricted to Nfc slopes. This is because different microclimatic conditions on differently facing slopes may result in different vegetation coverages since Sfc slopes have higher temperatures and receive more solar radiation (Wilson, 1970; Ueno, et al., 1989; Varley, et al., 1996). This could result in the higher moisture condition on Nfc slopes than on Sfc slopes according to Agro-Climatic Moisture Index defined by AgMet Rating Group (1985) and Alberta Soils Advisory Committee (1987). Thus, the moisture difference mainly controls the distribution of trees on N- and Sfc slopes, which in turn reflects different moisture conditions on N- and Sfc slopes.

4.8 Conclusions

Tree coverage percentage on the Nfc slopes on the Battle River is significantly larger than on the Sfc slopes (Figure 4.1). The higher tree coverage on the Nfc slopes indicates that the Nfc slopes have higher moisture content than on the Sfc slopes. Statistical results (Table 4.3) indicate that Nfc slope is about 63% covered, while the Sfc slope is only 27%, on the average. The moisture difference reflected by tree cover difference on the N- and Sfc slopes on the Battle River was modelled in Chapter 3.

In addition to the differences of tree cover percentage, the physical properties, such as height, and species distribution on Nfc slopes are significantly different from the Sfc slopes as well. Following gradual change of aspects of N- and Sfc slopes, the properties on both N- and Sfc slopes also change correspondingly. These property changes indicate that variation of slope aspects affects the difference of tree species and physical properties. The changes and the differences may be directly caused by solar radiation and soil moisture conditions controlled by different slope aspects.

The significantly different tree covers between N- and Sfc slopes on the Battle River gives a strong indication of moisture differences on N- and Sfc slopes. Moisture condition in turn may control landslide activities.

Trees and shrubs are also dominantly established on the Nfc slope on the Red Deer River, and even on the right side of the Bow River, there are still patches of shrubs, but not on the left side. The preferred establishment of vegetation on the Nfc slopes in the Battle River and Red Deer valleys, and on the right valley side of the Bow River, reveals that different moisture conditions occur on slopes facing differently. Higher moisture conditions correspond to the higher vegetation cover. Differences of moisture conditions could result in differing landslide incidences.

Slope angles on the Battle River vary in a very narrow range (4^0-10^0) which is a good indication of the slope status of abandonment. The slope profile on the Battle River may be explained by Hutchinson's (1967) slope model because of the soft material, shale, involved in landsliding, rotational and retrogressive sliding mechanisms and climate on the Battle River.

The angles of abandoned slopes on the three river sections measured are almost the same. This may demonstrate that the colluvial materials are essentially non-cohesive ($c' = 0$) and the maximum angle at which the hillslope is stable against landsliding is equal to the angle of residual friction of the soil ($\beta = \varphi_r$) (Selby, 1993, p.362). The consistency of the abandoned slope angles on the three rivers also indicates the validity of the measurements of slope angles, and shows that the materials in the three sections of the three rivers are simiar.

Steep, active slope angles measured on the outside of river meanders were measured on the N- and Sfc slopes of the Red Deer River and on the right and left sides of the Bow River. The steepness of the angles is quite different from the

Red Deer River and the Bow River, and the angle on the Red Deer River is lower (30^0) than the angle on the Bow River (35.1^0). The difference of the steep, active slope angles on the Red Deer River and the Bow River may indicate that the difference of moisture controls the steepness of the active steep slope angles while the slopes are under current river erosion.

Slope angles were systematically measured on the Battle River, Red Deer River and Bow River. The interval between every two measurements is 400 m. The average angles on the Nfc slopes are higher than on the Sfc slopes in the sections of the Battle River and the Red Deer River, but the angle on the right side of the Bow River is smaller than the angle on the left side. The differences may be accounted for by the control of erosion rate, climate and slope length (source area), as well as by the ability of removal of the colluvial material by rivers accumulated at the lower section of the slopes. Higher slopes will generate more accumulation of colluvial material at the lower section of the slopes if other conditions are the same, and the ability of the river to remove the accumulated material may be less than the rate of accumulation. Since the Sfc slopes are drier and have less vegetation cover, and they have higher rates of erosion, slope angles of lower sections of the Sfc slopes could be smaller than on the Nfc slopes. This could be the case on the Battle River and Red Deer River, but not on the Bow River because of shorter slopes on the Bow River.

The measurements of the slope angles indicate the interaction among the climate, slope length and the ability of river erosion to control slope angles. This study also shows that further systematic measurements may be necessary to analyze the relationship among slope, climate and river erosion.

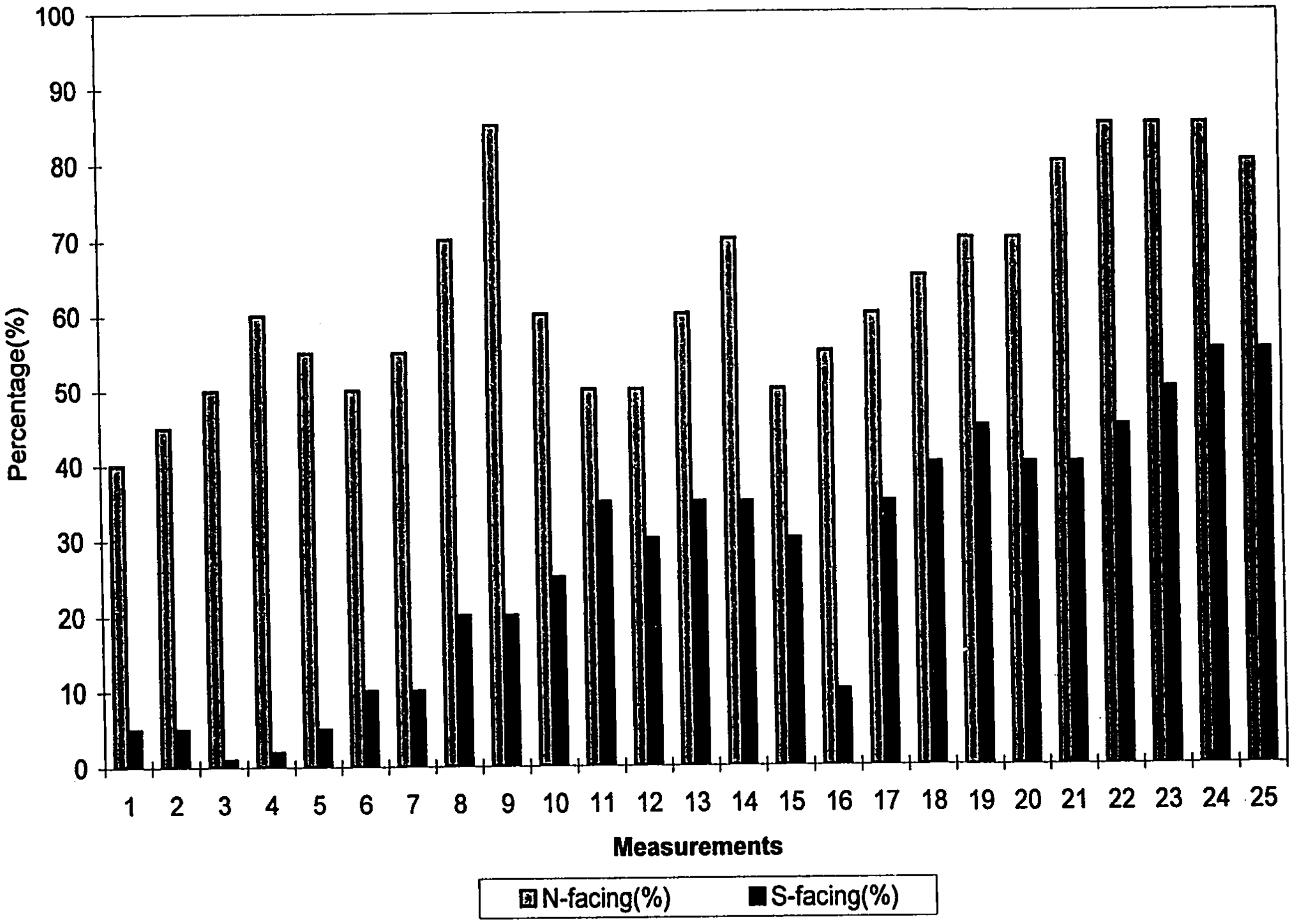


Figure 4.1 Tree cover on N- and Sfc slopes along the Battle River in Bearpaw Formation. Each pair of measurements covers 1 km.

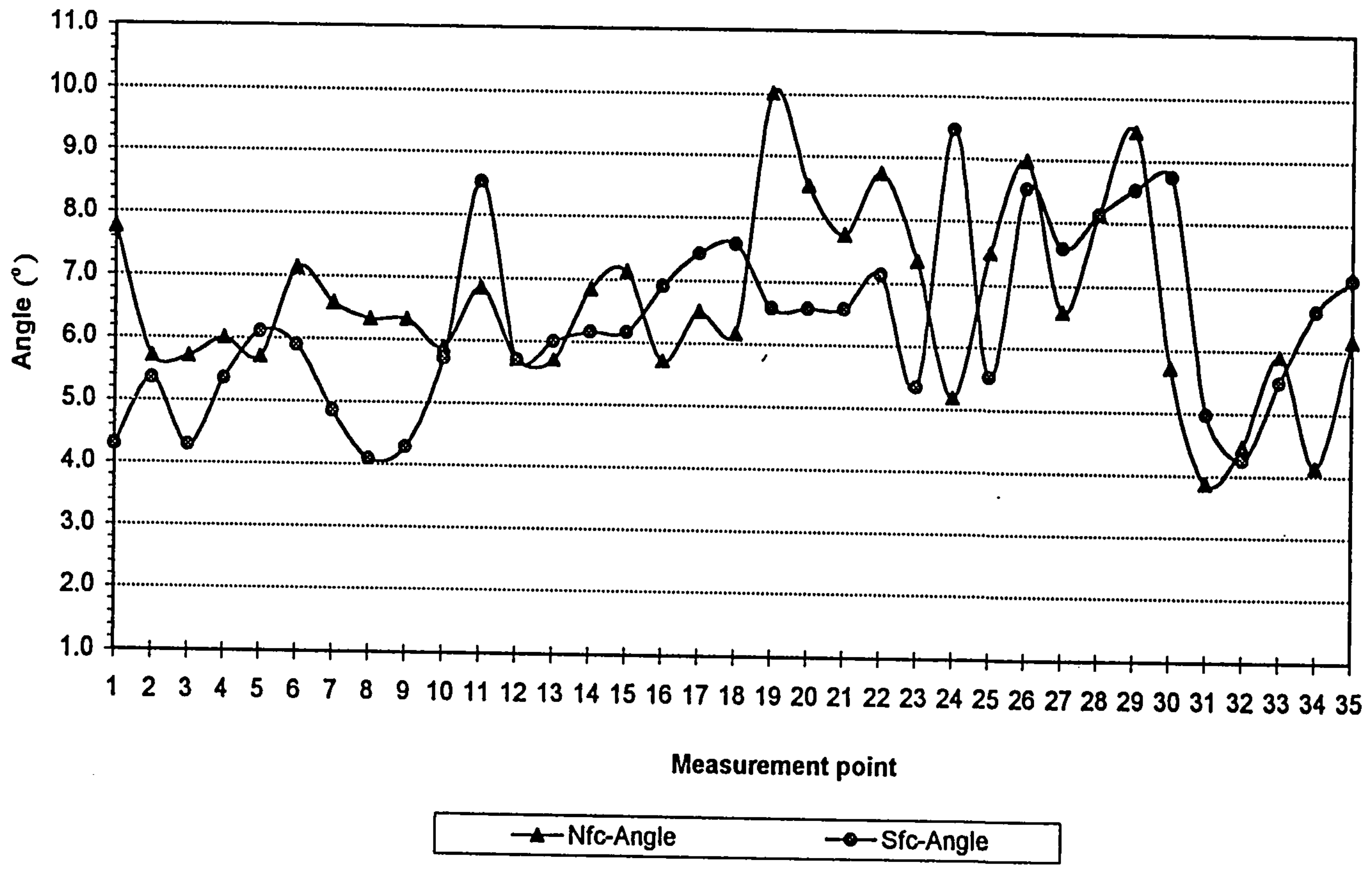


Figure 4.2 Slope angles on N and Sfc slopes on the Battle River in the Bearpaw Formation.

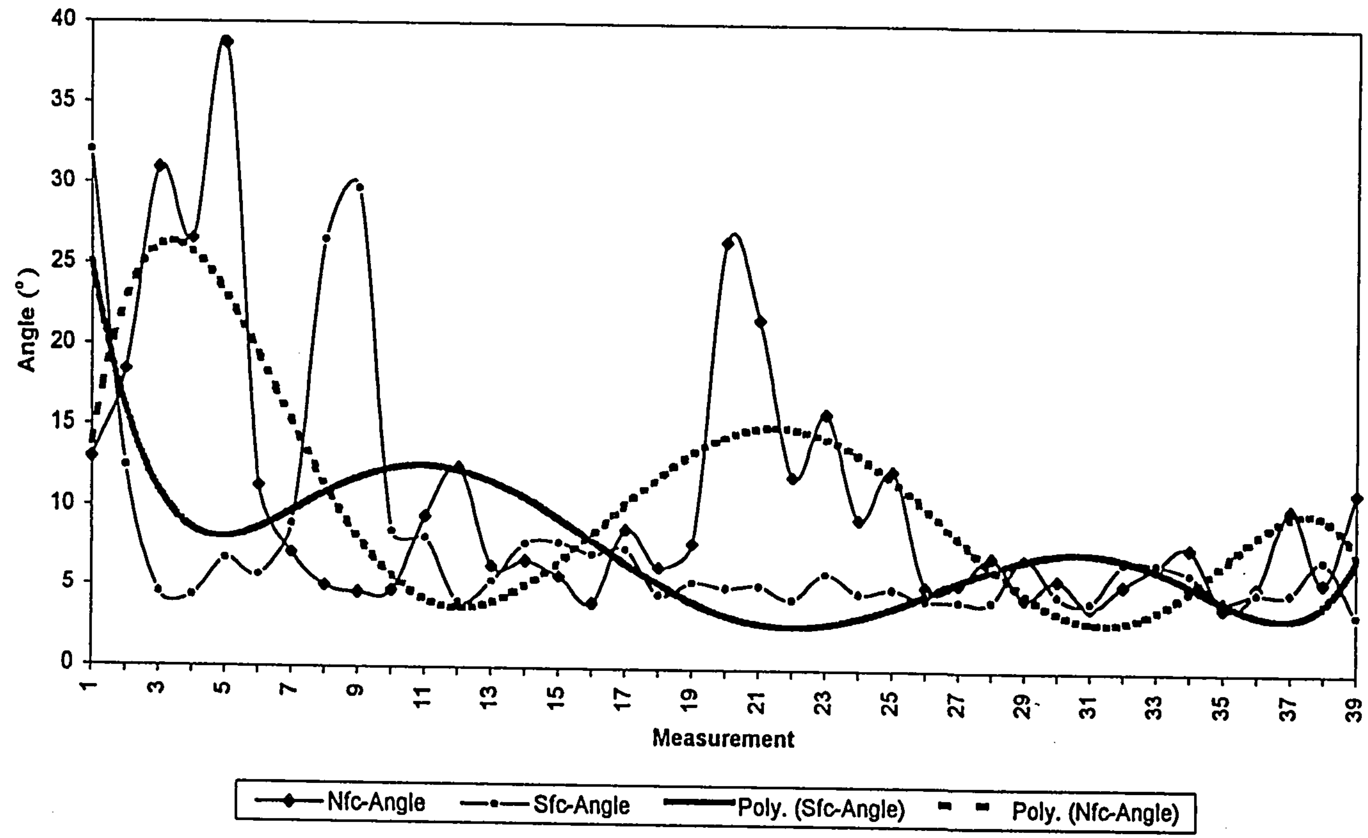


Figure 4.3 Plot of slope angles on N and Sfc slopes on the Red Deer River.

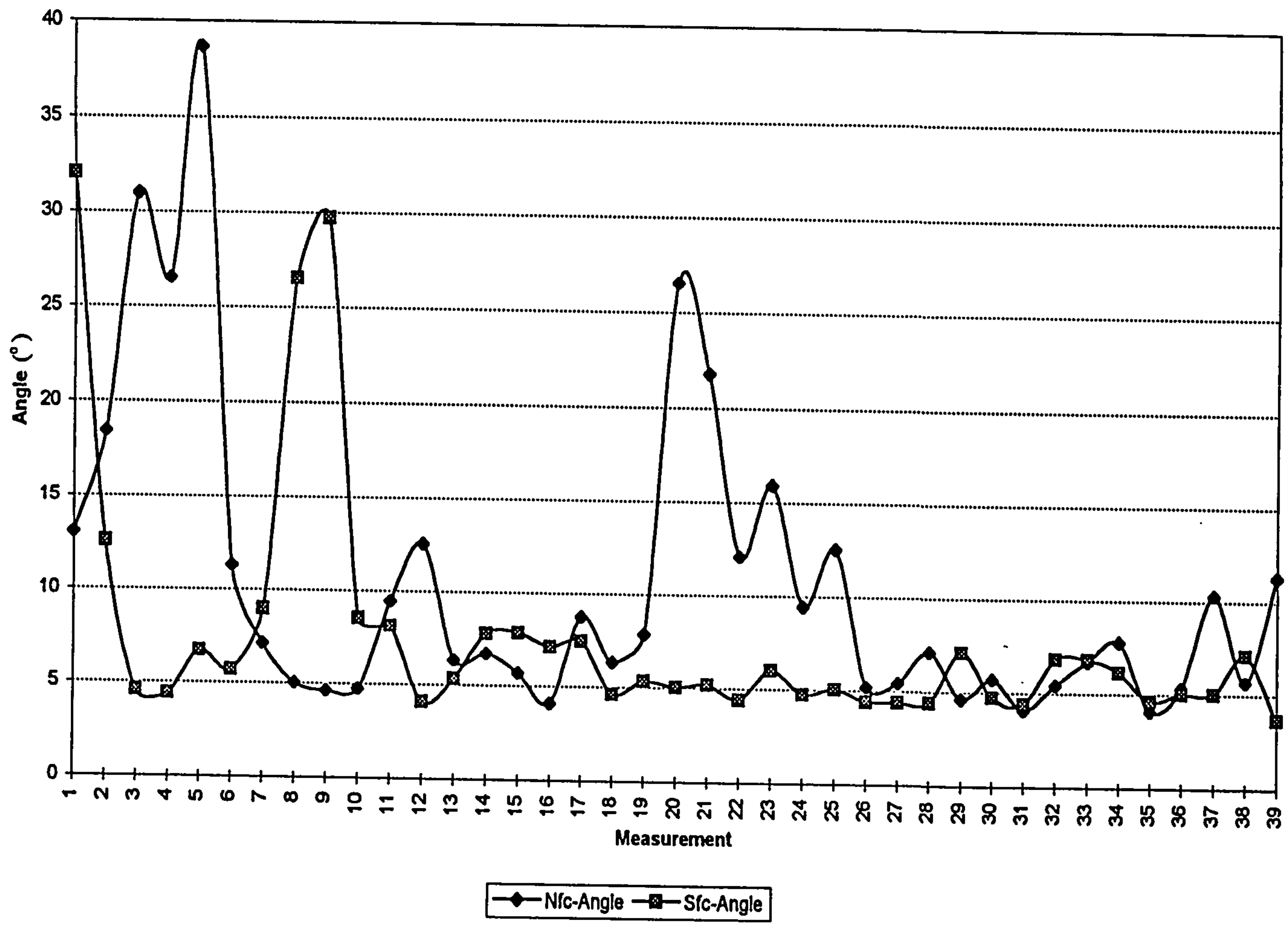


Figure 4.4 Scatter plot of slope angles on N and Sfc slopes on the Red Deer River.

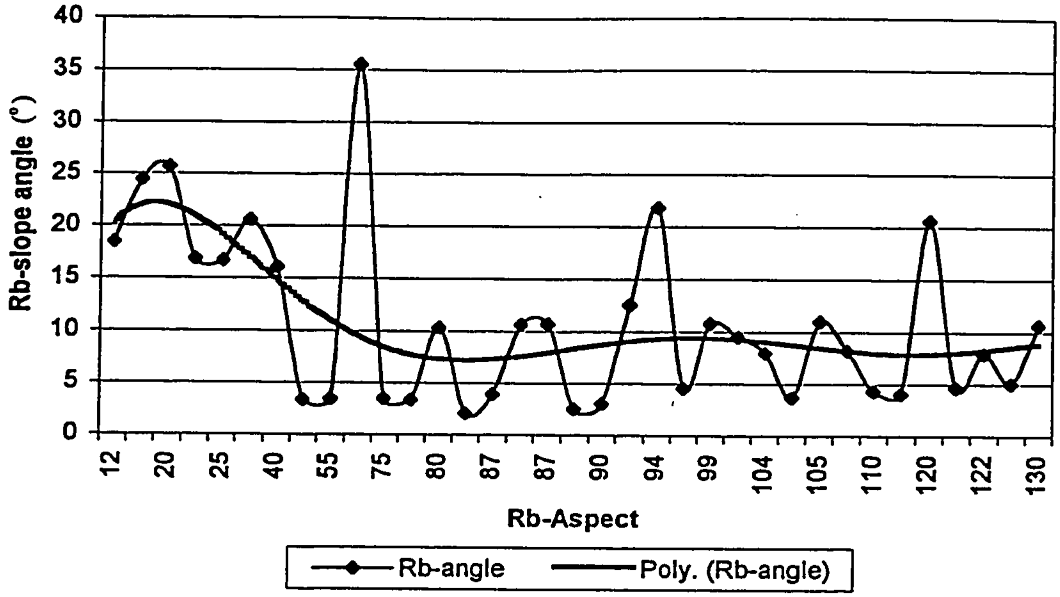


Figure 4.5 Slope angle on the right bank against its aspect on the Bow River.

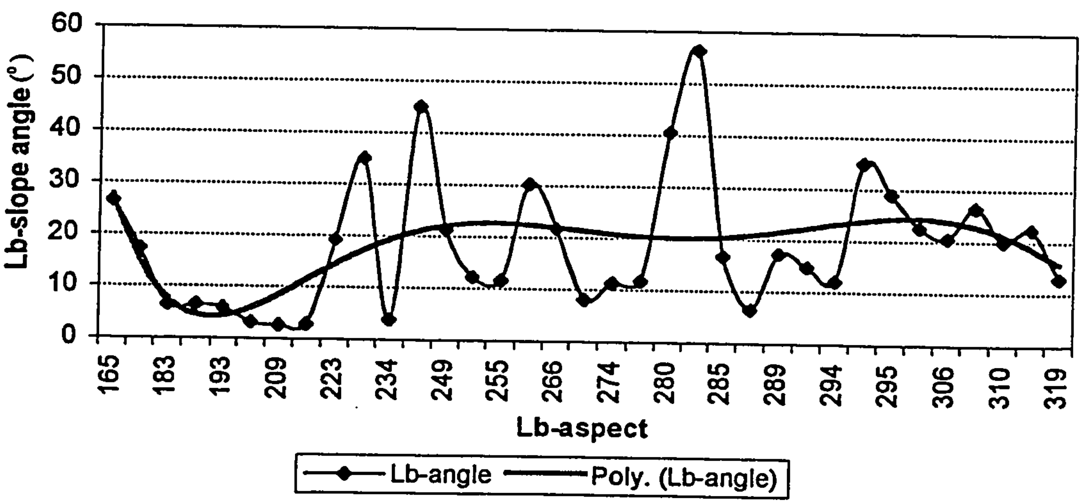


Figure 4.6 Slope angle on the left bank against its aspect on the Bow River.

Chapter 5

Conclusions

5.1 Introduction

Conclusions for this thesis covered in this chapter are in the same sequence as the thesis. Chapter 5.2 focuses on landslide incidence on north-facing (Nfc) and south-facing (Sfc) slopes from the Battle River to the Red Deer River and to the Bow River; the variation of the incidence from river to river is also discussed. Chapter 5.3 gives conclusions on the differences of direct short-wave input and moisture index between Nfc and Sfc slopes; modelled direct short-wave radiation, *PE* (Potential Evapotranspiration), and AgM Indices (Agro-Climatic Moisture Index) on Nfc and Sfc slopes are discussed in detail. Chapter 5.4 concludes the differences of tree cover, vegetation and slope angle on Nfc and Sfc slopes. Finally, further work is discussed in Chapter 5.5.

5.2 Landslide incidence on North- and South- facing slopes

This study has shown that in the three sections of the Battle, Red Deer and Bow Rivers in the same geologic formation, landslide incidence significantly decreases from the Battle to Red Deer and to Bow Rivers, and also the incidences significantly decrease from Nfc to Sfc slopes in the sections from the Red Deer and the Bow Rivers. The average incidences are 96% in the section of the Battle River, 68% in the section of the Red Deer River and 29% in the section of the Bow River. The average landslide incidences mapped in the three sections along the three rivers have resulted in much higher values than the incidences mapped by previous researchers. This may be explained by more detailed and focused mapping in the study area, especially field investigation and verification.

The separation of landslide incidences on N- and Sfc slopes has yielded significant difference of the incidences on slopes facing different directions. The average decrease of landslide incidence from the N- and Sfc slopes is 21% in the section of the Red Deer River and 35% in the section of the Bow River. These differences have given a strong incentive to further investigate the causes of the differences of landslide incidences on N- and Sfc slopes in the study area.

Various statistical results have showed that landslide incidence is significantly higher on Nfc slopes than on Sfc slopes in the sections of the Red Deer and the Bow Rivers. Pairwise statistical analysis has also showed that any incidence in a 45^0 sector of the slope aspect in the range of 90-180-270° (Nfc) is significantly different from incidence in the opposite sector in the range of 270-360-90° (Sfc). Differences of the incidences between every pair within each of the ranges (Nfc or Sfc) are not significant.

5.3 Direct short-wave radiation, *PE* (Potential Evapotranspiration), and AgM Moisture Indices on N- and Sfc slopes

Solar radiation is acknowledged to be an important variable controlling the hydrology, meteorology, biology and geomorphology of slope processes. Although the computation of short-wave radiation is relatively straightforward for a horizontal surface, in many physical situations, the influence of the topographic characteristics of the slope angle and its aspect need to be taken into account. Direct short-wave radiation is the major driving force for the variations in the rest of the energy balance components, thus leading to variations in the local climate on Nfc and Sfc slopes.

Direct short-wave radiation on N- and Sfc slopes along the three river sections has been modelled based on the average latitude, longitude, slope aspect and slope angle in each of the three river sections, as well as Julian days and time zone in the study area. The location, defined by latitude and longitude, is chosen at the centre of each of the river sections. The modeled results show that the direct short-wave radiation in summer time on Nfc slopes is up to 14.3% less than on horizontal surfaces, while on Sfc slopes it is up to 14.3% more than on horizontal surfaces. The difference between the N- and Sfc slopes is doubled (28.6%). The difference is the smallest during summer time, and it substantially increases beyond summer time. For example, the direct short-wave radiation on the Nfc slope of the Bow River in September is 40% less than on an horizontal surface, which gives a difference between N- and Sfc slopes of 80%.

The difference of short-wave radiation between N- and Sfc slopes is the cause of the moisture difference on N- and Sfc slopes of a river. Based on the modelled direct short-wave radiation, potential evapotranspiration (*PE*) and Agro-Climatic Moisture (AgM) Indices in the three river sections were modeled on flat surfaces, N- and Sfc slopes. The modeled results show the potential differences of *PE* and AgM Index on N- and Sfc slopes during summer months. Based on the differences, the N- and Sfc slopes in one study area could be considered as different ecoregions by the criteria of climatic parameters used by Strong and Leggat (1992).

In the water-limited study area, the difference of *PE* on the N- and Sfc slopes predicts a higher rate of net water loss on Sfc slopes. As a consequence, Sfc slopes should be drier than Nfc slopes, or the Nfc slopes have higher moisture content than on the Sfc slopes. A maximum moisture difference between N- and Sfc slopes is about 10% described in the in the Climatic Classification User's Manual for the semiarid region of southern Alberta (Version 2.0) (Northern Agricultural Research Centre, 1993). This manual also refers to the moisture difference on N- and Sfc slopes as moisture Reward and Penalty from an agricultural point of view. Higher moisture content is one of the crucial factors in causing landslides, especially in soft materials such as weathered shale in the study area.

The modelled total *PE* on horizontal surfaces, N- and Sfc slopes on the three river sections during summer time is over 500 mm, which is much higher than the total summer precipitation on each of the three rivers. The difference of *PE* between the N- and Sfc slopes on the Battle River during the summer time is 26.6 mm, on the Red Deer River is 39.3 mm and on the Bow River is 51.3 mm. The difference gradually increases from the north to the south in the study area, which indicates that the difference of moisture conditions between N- and Sfc slopes in the study area increases from north to south. This is consistent with the differences of landslide incidences between N- and Sfc slopes from the Red Deer River to the Bow River.

The modelled total *PE* on horizontal surfaces from the Battle River to the Red Deer River and to the Bow River during summer time is 516.2, 526.5 and 555.0 mm, respectively. The difference of *PE* on the horizontal surfaces from the Red Deer River to the Bow River is 28.5 mm, while the difference of the *PE* from the Battle River to the Red Deer River is 10 mm. The increase of *PE* on the horizontal surfaces reflects one of the important factors, latitude, in the study area in controlling the moisture conditions in addition to the maximum and minimum temperatures at the location.

The modelled AgM Index on a flat surface is –479.1 mm on the Bow River, while on the Red Deer River and the Battle River on horizontal surfaces it is –55.2 and –258.9 mm, respectively. It is clear that the Bow River area has the poorest moisture condition, while the Battle River has the best and the Red Deer River is in the middle in terms of Agro-Climatic Indices in the study area during summer time. The difference between the Bow River and the Red Deer River is 123.9 mm and between the Red Deer River and the Battle River is 96.3 mm. The differences may be an important reason why the landslide incidences among the three river sections are significantly different because other conditions are the same or similar.

The modelled results of AgM Indices on N- and Sfc slopes are also significantly different. The difference is 60.3 mm from the Nfc slope to Sfc slope on the Bow River, while the difference on the Red Deer River is 45 mm and on the Battle River is 30.4 mm. The differences gradually increase from north to south in the study area. The increase of moisture deficit from north to south across the study area is probably an important reason why the landslide incidences on the Nfc slopes on the Red Deer River and Bow River are significantly higher than on the Sfc slopes.

Direct short-wave radiation, *PE*, and AgM Index are modelled in the prime growing season, during which the sun has the highest zenith angle, and therefore the radiation difference on N- and Sfc slopes is at the minimum. Higher radiation differences on N- and Sfc slopes should occur if the time period is extended beyond August or May. A modelled example of the short-wave radiation difference in September (Chapter 3.5) shows that the difference of the direct short-wave radiation in September on Sfc slopes is almost two times of the radiation on the Nfc slopes on the Bow River.

The modelled *PE* and AgM Indices should be considered as minima because the maximum and minimum temperatures on N- and Sfc slopes are considered as the same in the modelling but studies have shown that Sfc slopes have higher temperatures than Nfc slopes. Such higher temperatures increase evaporation when moisture is available.

Solar radiation difference on N- and Sfc slopes is the primary cause for the variation in the local climate in the ways modelled. Hydrologic activity is likely to vary as a result of different rates of evapotranspiration, and lengths of snow-cover retention. The persistence of this is frequently reflected in vegetation distribution (Henderson-Sellers and Robinson, Ch. 6, 1994).

5.4 Tree cover, vegetation and slope angle on N- and Sfc slopes

The difference of moisture conditions on N- and Sfc slopes is further reflected by the differences of tree cover, vegetation and slope angles on the N- and Sfc slopes. Significant and relatively continuous tree cover is limited to the Battle River valley in the study area. Patches of trees appear along the Red Deer River valley, but basically there are no trees along the Bow River valley. Tree cover mapping on the Battle River indicates that Nfc slope has significantly higher coverage than the Sfc slope. Statistical results indicate that Nfc slope is 63% covered, while the S-facing slope is only 27%, on the average. The tree cover difference between the N- and Sfc slopes shows a consistency with the modelled climatic variables on the Battle River (Chapter 3.2 and 3.4).

In addition to the difference of tree coverages on N- and Sfc slopes on the Battle River, the physical characteristics of the trees and species distribution on N- and S-facing slopes follow the gradual change of slope aspects on the Battle River. These differences may be directly caused by the solar radiation and soil moisture conditions controlled by slope aspect on the Battle River in the study area.

The significant difference of tree cover between N- and S-facing slopes on the Battle River gives a strong indication of moisture difference on N- and S-facing slopes, which in turn strongly influences the landslide activities.

Trees and shrubs are established on the N-facing slopes of the Red Deer River valley, and even on the right side (or southwest) of the Bow River; there are still patches of shrubs, but not on the left side. The preferred establishment of vegetation on the Nfc slopes on the Battle River, the Red Deer River and on the right side of the Bow River demonstrates that higher moisture conditions are consistent with the higher vegetation cover. The different moisture conditions could result in different landslide incidences in the study area.

Abandoned slopes measured on the three river sections are about 6.4°. This is a demonstration that the fine colluvial materials are essentially non-cohesive ($c'= 0$) and the maximum angle at which the hillslope is stable against landsliding is equal to the angle of residual friction of the soil φ_r. The consistency of the abandoned slope angles on the three rivers also indicates the validity of the measurements of slope angles, and shows that the materials in the three sections of the three rivers are the same.

Steep, active slopes on the outside of river meanders were measured on the N- and S-facing slopes of the Red Deer River and on the right and left sides of the

Bow River. The average angle on the Red Deer River is lower (30°) than the angle on the Bow River (35.1°). The higher, steep and active slope angles on the Bow River may indicate that lack of moisture controls the steepness of the active steep slope angles while the slopes are under the current river erosion.

The differences may be accounted for by the interaction among factors of climate, slope length (source area), as well as the ability of removal of the colluvial material by rivers accumulated at the lower section of the slopes. Higher slopes will generate more accumulation of colluvial material at the lower section of the slopes if other conditions are the same, and the ability of the river to remove the accumulated material may be lower than the rate of accumulation. Because the Sfc slopes are drier and have less vegetation cover, and they have higher rates of erosion, slope angles at lower sections of slopes on the Sfc slopes should be smaller than on Nfc slopes. This may be the case on the Battle River and the Red Deer River, but not on the Bow River because of shorter slopes on the Bow River.

The mapping of landslide incidence showed that the terraces on the section of the Red Deer River are limited only to the Nfc slope, and they do not occur on the Sfc slope. It could be that a higher erosion rate operating on the Sfc slope has eroded the terraces away, but not on the Nfc slope because of lower erosion rates there.

5.5 Further work

This thesis has revealed some more interesting questions that are beyond the topic of this thesis, but worthy of further study.

The modelling of direct short-wave radiation on N- and Sfc slopes was based on the average slope angles and aspects on the N- and Sfc slopes for a river section. Further calculation is desirable to manipulate the variation of short-wave radiation following the variation of slope aspects and slope angles of a river valley. This could be done by using GIS to map the spatial variation of the modelled values following the changes of location, slope aspect and angle in the study area as well as in southern Alberta.

The basic vegetation study on N- and Sfc slopes on the three rivers indicates different moisture conditions on differently facing slopes. More work could be done to demonstrate the variation of vegetation cover following the change of slope aspects on the same side in a river valley. This could yield more significant results to analyze the sensitivity of the variation of slope aspects on the vegetation.

The slope angle study has given interesting results, but field measurement is necessary to further verify the results, especially on abandoned slopes covered by colluvial materials. As well, samples need to be collected on the abandoned colluvial material to test friction angles of colluvial materials to find out if the measured slope angle and the friction angle are the same.

References

AgMet Rating Group, 1985. Agroclimatic classification for Alberta. Alberta Agriculture, Agrometeorology Advisory Committee, Edmonton.

Aisenshtat, B. A., 1966. Investigations on the heat budget of central Asia. In snowremennye problemy klimatologii (M. I. Budyko, ed.). Meteorol. Gidrol., Ledningrad, 83-129. Referred to by Oke (1987).

Alberta Forestry, Lands and Wildlife, 1991. Alberta vegetation inventory standards manual, Version 2.1, Alberta Environmental Protection, Resource Data Division, Edmonton Alberta. 53pp.

Alberta Soils Advisory Committee, 1987. Land capability classification of arable agriculture in Alberta. Edited by W. W. Pettapiece. Alberta Agriculture, Edmonton.

Alberta vegetation inventory standards manual, 1991. Alberta Forestry, Lands and Wildlife, Land Information Services Division. Edmonton, Alberta.

Allan, J. A., and Sanderson, J. O. G., 1925. Geological Maps of Rosebud sheet. Scale 1: 190,080. Scientific and Industrial Research Council of Alberta.

Allan, J. A., and Sanderson, J. O. G., 1946.General Geology of Red Deer and Rosebud Sheets; Scale 1: 253,440. Alberta Research Council.

Allan, J. A., and Sanderson, J. O. G., 1945. Geology of the Red Deer River and Rosebud sheets, Alberta Research Council. Alberta, Report 13, p. 109.

Arvidson, W. D., 1972. An airphoto study of landslides along the Red Deer River and Bow Rivers in Alberta. Internal Report, Department of Civil Engineering, University of Alberta. Edmonton, 69p.

Babcock, E. A., 1973. Regional jointing in southern Alberta. Canadian Journal of Earth Science, 10: 1769-1781.

Bayrock, L. A., 1958. Glacial geology of the Alliance-Brownfield district. Alberta Research Council, Edmonton, Preliminary Report 57-2, 45p.

Bayrock, L. A., 1960. Surficial Geology of the Wainwright area (east half), Alberta. Alberta Research Council. Edmonton. Preliminary Report 67-4. 10pp.

Bayrock, L. A., 1967. Surficial Geology of the Wainwright Area, Alberta;. Scale 1: 63,360. Alberta Research Council.

Beaty, C. B., 1972a. Geographical distribution of post-glacial slumping in southern Alberta, Canadian Geotechnical Journal, 9: 219-224.

Beaty, C. B., 1972b. The effect of moisture on slope stability: A classic example from southern Alberta, Canada. Journal of Geology, 80: 362-366.

Beaty, C. B., and Young, G. S., 1975. The landscapes of southern Alberta--A regional geomorphology, University of Lethbridge.

Bolduc, J., Cruden, D. M., Leung, S., Sonnenberg, R., and Thomson, S., 1988. Landslide incidence in Alberta, South of 54^0 N. Research Management Division, Alberta Environment, RMD 84/22, 58pp.

Borneuf, D., 1972. Hydrogeology of the Drumheller area, Alberta. Research Council of Alberta, Edmonton, Report 72-1.

Brooks, F. A., 1959. Introduction to Physical Microclimatology. University of California, Davis.

Broscoe, A. J., and Barton, R. H., 1959. Geomorphology of the Drumheller-Morrin area, South-Central Alberta, Ninth Annual Field Conference, Alberta Society of Petroleum Geologists.

Brunsden, D., 1984. Mudslides. In: Slope instability. Edited by D. Brunsden, and D. B. Prior, Wiley, Chichester, p. 363-418.

Budel, J. 1982. Climatic geomorphology. Princeton University Press. Princeton, New Jersey.

Buffo, J., Fritschen, L. J., and Murphy, J. L., 1972. Direct solar radiation on various slopes from 0 to 60 degrees north latitude, United States Forest Service Research Paper, PNW-142. 74pp.

Campbell, C., 1997. Postglacial geomorphic response and environmental change in southeastern Alberta, Canada. Ph.D thesis, Department of Earth and Atmospheric Sciences, the University of Alberta.

Campbell, C., and Campbell, I. A., 1997. Calibration, review, and geomorphic implications of postglacial radiocarbon ages in southeastern Alberta. Geographie physique et Quaternaire, 48: 207-214.

Carlson, V. A., 1969. Bedrock Topography of the Drumheller Map-Area, Alberta. Scale 1: 250,000. Alberta Research Council.

Carlson, V. A., 1970. Bedrock Topography of the Medicine Hat Map-Area, Alberta, Scale 1: 250,000. Alberta Research Council, Edmonton.

Carlson, V. A., 1972. Bedrock Topography of the Wainwright Map-Area, Alberta: West of fourth meridian. Alberta Geological Survey.

Carlson, V. A., Turner,W. R., and Geiger, K. W., 1969. A gravel and sand aquifer in the Bassano-Gem region, Alberta. Alberta Research Council, Edmonton, Report 69-4.

Carson, M. A., 1976. Mass-wasting, slope development and climate. In: Geomorphology and Climate. Edited by E. Derbyshire, London: Wiley.

Chandler, R. J., 1982. Lias clay slope sections and their implications for the prediction of limiting or threshold slope angles. Earth Surface Processes and Landforms, 7:427-38.

Chase, M. E., 1969. Airborne remote sensing for groundwater studies in prairie environment. Canadian Journal of Earth Sciences, 6: 737-741.

Chlachula, J., 1996. Geology and Quaternary environments of the first preglacial palaeolithic sites found in Alberta, Canada. Quaternary Science Review, 15: 285-314.

Churchill, R. R., 1981. Aspect-related differences in badlands slope morphology. Annals of the Association of American Geographers, 71: 375-388.

Cremeans, D. W., 1992. Aspect and slope position effects on moisture regime and properties of forest soils in eastern Kentucky. Ph.D thesis, the University of Kentuky, Lexington, Kentucky.

Crozier, M. J. 1986. Landslides: causes, consequences, and environment. Croom Helm, London.

Cruden, D. M. 1993. General Report: Slope stability and protection. International Symposium on Hard Soil-Soft Rocks. Athens, Greece, p.38.

Cruden, D. M. 1996. An inventory of landslides in Alberta, Canada. Proceedings of the Seventh International Symposium on Landslides. Balkema, Rotterdam. 3: 1877-82.

Cruden, D. M., Sonneberg, R., and Thomson, S., 1991. An overview of landslide incidence in central and southern Alberta. Proceedings of 41st Canadian Geotechnical Conference, p. 282-291.

Cruden, D. M., and Thomson, S., 1987. Exercises in terrain analysis. The Pica Pica Press. Edmonton, AB, Canada.

Cruden, D. M., Thomson, S., Kim H. J., and Peterson, A. E., 1995. The Edgerton landslides. Canadian Geotechnical Journal, 32: 989-1001.

Cruden, D. M., Keegan, T. R., and Thomson, S., 1993. The landslide dam on the Saddle River near Rycroft, Alberta. Canadian Geotechnical Journal, 30: 1003-1015.

Cruden, D. M. and Varnes, D. J., 1996. Landslides-investigation and mitigation. Special Report 247. Transportation Research Board. National Research Council.

Cruden, D. M., de Lugt, J. S., Lindstrom, K., and Thomson, S., 1989. Landslide incidence in Alberta. Report to Design and Construction Branch, Alberta Environment, Edmonton. 87p.

Davenport, D. C., 1967. Variation of evaportation in time and space, 1. Study of diurnal changes using evaporimeters and grass lysimiters. Journal of Hydrology, 5: 312-328.

Dearman,W. R., and Fookes, P. G., 1974. Engineering geological mapping for civil engineering practice in the United Kingdom. Quarterly Journal of Engineering Geology. 7: 223-256.

Dohrenwend, J. C., 1978. Systematic valley asymmetry in the central California Coast Ranges. Geological Society of America Bulletin. 89: 891-900.

Doornkamp, J. C., 1986. Climate and weathering. In: A Handbook of Engineering Geomorphology, Edited by P. G. Fookes and P. R. Vaughan. Chapman and Hall, New York.

Drinkwater, T. A., Huestis, E. S., Istvanffy, D. I., Klawe, J. J., Laycock, A. H., and Wonders, W. C., 1969. Atlas of Alberta. University of Alberta Press. Edmonton, AB. 158pp.

Dyke, A. S., and Prest, V. K., 1987. Wisconsinan and Holocene retreat of the Laurentide Ice Sheet. Geological Survey of Canada, Map 1702A, scale 1: 5 000 000.

Ecoregions Working Group. 1989. Ecoclimatic regions of Canada, first approximation. Environment Canada, Canada Committee on Ecological land Classification, Ottawa, Ontario. Ecological Land Classification Series, No. 23.

Environment Canada, 1987. Climatic Atlas Climatique-Canada. 7 map series. 1984-1989.

Environment Canada, 1994. Canadian monthly climate data and 1961-1990 normals.

Evans, D. J. A., and Campbell, I. A., 1995. Quaternary stratigraphy of the buried valleys of the lower Red Deer River, Alberta, Canada. Journal of Quaternary Science, 10: 123-148.

Farvolden, R. N., 1963. Bedrock channels in southern Alberta. In: early Contributions to the groundwater hydrology of Alberta. Research Council of Alberta, Bulletin, 12: 63-75.

Ferguson, H. L., Cork, H. F., Anderson, R. L., Mastoni, S., and Weisman, B., 1971. Theoretical clearsky effective insolation over a small mountain basin. Climate Study, 21, 45pp.

Francis, S, C., 1987. Slope development through the threshold concept. In: Slope Stability. Edited by M. G. Anderson and K. S. Richards, Wiley, Chichester.

Fulton R. J. (Editor), 1989. Quaternary geology of Canada and Greenland. Geological Survey of Canada, Ottawa.

Geological Survey of Canada, 1960. Surficial Geology Map of Red Deer-Stettler. Scale 1: 253,440.

Geiger, K. W., 1967. Bedrock Topography of the Gleichen Map-Area, Alberta. Scale 1: 250,000. Alberta Research Council.

Gilbert, E. G., and Wolfe, J. N., 1959. Soil moisture investigations at Neotoma, a forest bioclimatic laboratory in central Ohio. The Ohio Journal of Science 59(1): 38-46.

Goulden, M. R., and Sauchyn, D. J., 1986. Ages of rotational landslides in the Cypress Hills, Alberta-Saskatchewan. Geographie physique et Quaternaire, 40: 239-248.

Gravenor, C. P., 1956. Glacial geology of the Castor district. Alberta Research Council, Report 56-2.

Gravenor, C. P., and Bayrock, L. A., 1955. Glacial geology of the Coronation district. Alberta Research Council, Report 55-1.

Green, R., 1972. Geological map of Alberta. 1: 1,267,000. Research Council of Alberta. Edmonton, AB.

Hare, T. K., and Thomas, M. K. 1979. Climate Canada. John Wiley, Toronto.

Henderson-Sellers A., and Roberson A. P., 1994. Radiation budget and energy systems of the earth. Contemporary Climatology. John Wiley, New York.

Hickman, M., and Schweger, C. E., 1993. Late glacial-early Holocene palaeosalinity in Alberta, Canada-climate implications. Journal of Paleolimnology, 8: 149-161.

Hutchinson, J. N., 1973. The response of London clay cliffs to differing rates of toe erosion. Geologia Applicata E Idrogeologia. Bari, 3: 221-239.

Hutchinson, J. N., 1967. The free degradation of London clay cliffs. Proceedings of the Geotechnical Conference. Oslo, 1: 113-118.

Irish, E. J., 1971. Geology of Southern Plains of Alberta. Scale 1: 500,000. Geological Survey of Canada.

Jerzykiewicz, T., 1997. Stratigraphic framework of the Uppermost Cretaceous to Paleocene strata of Alberta. Geological Survey of Canada Bulletin 510.

Johnson, D., Kershaw, L., Mackinnon, A, and Pojar, J., 1995. Plants of the Western Boreal Forest and Aspen parkland. Lone Pine Publishing. Edmonton, AB, Canada.

Kennedy, B., 1976. Valley-side Slopes and Climate. In: Geomorphology and climate, Edited by E. Derbyshire. London, Wiley.

Kenney, C., 1984. Properties and behavior of soils relevant to slope instabilities. In Slope Instability, Edited by D. Brunden, and D. Prior. John Wiley, Chichester, U.K.

Koppen, W. 1931. Grundriss der Klimakunde. De Gruyter, Berlin.

Larson, J. A., 1940. Site factor variation and responses in temporary forest types in northern Idaho. Ecological Monographs, 10: 1-54.

Link, K. N., 1980. An Introduction to Atmospheric Radiation. New York. Academic Press.

Liou, K. D., 1980. An introduction to atmospheric radiation. New York Academic Press. International Geophysics Series 26.

Longley, R. W., 1967. Climate and weather Patterns. In: Alberta, A Natural History. Edited by W. G. Hardy, Chapter 3.

Longley, R. W. 1972. The climate of the prairie provinces. Environment Canada. Climatological studies, No. 13.

Mac Hattie, L. B., and McCormack, R. J., 1961. Forest microclimate: a topographic study in Ontario. Journal of Ecology. 49: 301-323.

Meyboom, P., 1960. Geology and groundwater resources of the Milk River sandstone in southern Alberta. Memoir - Research Council of Alberta.

Miller, R., 1985. Multiple comparisons. In: Encyclopedia of Statistical Sciences, Vol. 5, Edited by S. Kotz, and N. L. Johnson, New York, John Wiley & Sons, Inc.

Nesby, R., 1997. Alberta vegetation inventory standards manual Version 2.2, Alberta Environmental Protection, Resource Data Division, Edmonton, Alberta.

Northern Agricultural Research Centre, 1993. Climate classification system version 2.0, User's manual. Agriculture and Agri-Food Canada, Beaverlodge, Alberta, Canada.

Oke, T., 1987. Boundary layer climatology. Methuen, London and New York.

Ozoray, G., 1972. Structural control of morphology, Alberta. Alberta Geographer, 8: 35-42.

Parker, J., 1952. Environment and forest distribution of the Palouse Range in northern Idaho. Ecology, 33: 451-4561.

Papadakis, J., 1970. Climates of the world: Their classification, similitude, differences, and geographic distribution. Libro De Edicion, Argentina.

Paterson, J. R., 1996. The development of glacial Lake Bassano during the Late Pleistocene in southern Alberta. M.Sc. thesis, Dept. of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB.

Pawlowicz, J. G., and Fenton, M. M., 1995. Bedrock topography of Alberta, Map 226. Alberta Geological Survey, Edmonton.

Penman, H. L., 1948. Natural evaporation from open water, bare soil, and grass. Proceedings of Royal Society of London, Series A, 193: 120-145.

Pettapiece, W. W., 1987. Land capability classification of arable agriculture in Alberta, Alberta Soils Advisory Committee, Alberta Agriculture, Edmonton.

Phillips, D., 1990. The climates of Canada. Environment Canada, Ottawa, Ontario.

Radbruch-Hall, D. H., Colton, R. B., Davies, C. W., and Lucchitta, I., 1982. Landslide overview map of the Conterminous United States. Geological Survey Professional Paper 1183. United States Government Printing Office, Washington.

Rains, R. B., and Welch, J., 1988. Out-of-phase Holocene terraces in part of the North Saskatchewan River basin, Alberta. Canadian Journal of Earth Sciences, 25: 454-464.

Rains, R. B., Burns, J. A., and Young, R. R., 1994. Postglacial alluvial terraces and an incorporated bison skeleton, Ghostpine Creek, southern Alberta. Canadian Journal of Earth Sciences, 31: 1501-1509.

Radke, J. K., 1982. Managing early season soil temperatures in the northern corn belt using configured soil surfaces and mulches. Journal of Soil Science Society of America, 46: 1067-71.

Radke, J. K., Reicosky, D. C., and Voorhees, W. B., 1993. Laboratory simulation of temperature and hydraulic head variations. Journal of Soil Science Society of America, 57: 652-660.

Reid, I., 1973. The influence of slope orientation upon the soil moisture regime, and its hydromorphological significance. Journal of Hydrology, 19: 309-321.

Rib, H. T., and Liang, T., 1978. Recognition and Indentification. In: Landslides Analysis and Control, Special Report. Edited by R. L. Schuster, and R. J. Krizek. Transportation Research Board, National Research Council.

Russell, L. S., and Landis, R. W., 1940. Geology of the southern Alberta plains, Geological Survey of Canada, Memoir 221, p. 219.

Rutherford, R. L., 1939. Geological Map of Stettler, Alberta; Scale 1: 253,440. Department of Mines and Resources, Geological Survey of Canada.

Sauchyn, D., 1993. Postglacial evolution of the semiarid interior plains of Canada: A review, relevant concepts and a spatial framework. In: Glaciotectonics and mapping glacial deposits. Edited by J. S. Aber. Canadian Plains Research Center, Regina, pp. 201-214.

Sauchyn, D., 1994. Postglacial evolution of the semiarid interior plains of Canada: A review, relevant concepts and a spatial framework. In: Glaciotectonics and mapping glacial deposits. Edited by J. S. Aber. Canadian Plains Research Centre, Regina, p. 201-214.

Scott, J. S., and Brooker, E. W., 1968. Geological and engineering aspects of upper Cretaceous shales in western Canada. Geological Survey of Canada, Paper 66-37.

Selby, M. J., 1970. Slopes and Slope Processes. Hamilton, New Zealand, New Zealand Geographical Society, 59p.

Selby, M. J., 1993. Hillslope Materials and Processes. Second Edition. Oxford Univeristy Press, Oxford.

Shanks, W. D., and Norris, F. H., 1950. Microclimatic variation in a small valley in eastern Tennessee. Ecology, 31: 532-539.

Shetsen, I., 1987. Quaternary Geology, Southern Alberta. Alberta Research Council map, scale 1: 500,000.

Shetsen, I. 1990. Quaternary geology, central Alberta. Alberta Research Council, map, scale 1: 500 000.

Skempton, A. W., and Delory, F. A., 1957. Stability of natural slopes in London Clay. Proceedings of 4th International conference on Soil Mechanics. International Society for Soil Mechanics and Foundation Engineering (ISSMFE), London, Volume 2, p. 135-204.

Stalker, A. MacS., 1960. Surficial geology of the Red Deer – Stettler map area, Alberta. Geological Survey of Canada Memoir 306. Ottawa, ON.

Stalker, A. MacS., 1961. Buried valleys in central and southern Alberta. Geological Survey of Canada. Paper 62-32.

Stalker, A. MacS., 1965. Surficial geology, Bassano-Gleichen east half. Geological Survey of Canada, Preliminary Map, 5-1965.

Stalker, A. MacS., 1969. Quaternary stratigraphy in southern Alberta report 2: Sections near Medicine Hat. Geological Survey of Canada, Paper, 69-26.

Stalker, A. MacS., 1973. Surficial geology of the Drumheller area, Alberta. Geological Survey of Canada, Memoir 370.

Strong, W. L., and Leggat, K. R., 1981. Ecoregions of Alberta. Alberta Energy and Natural Resources, Edmonton. Technical Report No. T/4.

Strong, W. L., and Leggat, K. R., 1992. Ecoregions of Alberta. Alberta Forestry, Lands and Wildlife, Edmonton. Technical Report No. T/245.

Subcommittee on Biophysical Land Classification. 1969. Guidelines for biophysical land classification. Edited by D. S. Lacate. Canada Department of Fisheries and Forestry, Forest Service Publication 1264.

Sugden, D., 1973. Geomorphology since the creation and the flood: Geographical Management, 46: 34-40.

Swift, L. W., and Knoerr, K, R., 1973. Estimating solar radiation on mountain slopes. Agricultural Meteorology. 12: 329-336.

Thomson, S., and Bruce, I., 1978. An airphoto study of landslides along the North Saskatchewan River in central Alberta, Canada. Proceedings of 16th Annual Symposium on Engineering Geology and Soils Engineering. Boise, ID, p. 85-110.

Thomson, S., and Morgenstern, N. R., 1977. Factors affecting distribution of landslides along rivers in southern Alberta. Canadian Geotechnical Journal, 14: 508-523.

Thomson, S., and Morgenstern, N. R., 1979. River erosion and bank stabilization - North Saskatchewan River, Edmonton, Alberta. Canadian Geotechnical Journal, 16: 567-576.

Thornthwaite, C. W., 1933. The climates of the Earth. Geographical Review, 23:433-440.

Tokarsky, O., 1986. Hydrogeologic cross section M-M, Medicine Hat 72L. Alberta Environment, Water Resources Management Services, Edmonton.

Tokarsky, O., 1988. Buried valleys of Alberta. Alberta Technical Services Division, Hydrogeological Branch. Map, 1:2000000.

Toy, J. T., 1977. Hillslope form and climate. Geological Society of America Bulletin, 88: 16-22.

Trewartha, G. T., 1954. An Introduction to Climate. McGraw-Hill, Toronto.

Tricart, J., and Cailleux, A., 1972. Introduction to climatic geomorphology: London, Longman Group Ltd., London, 259pp.

Ueno, M., Sugimoto, Y., and Hirata, M., 1989. Effect of slope exposures on the growth of tall Fescue and Bahiagrass in subtropical region of Hyushu. XVI International Grassland Congress. Nice, France.

Vance, R. E., and Wolfe, S. A., 1996. Climate. In: Landscapes of the Palliser Triangle: Guidebook for the Canadian geomorphology field trip. Edited by D. S. Lemmen. Canadian Association of Geographers 1996 Annual Meeting, Saskatoon, p. 8-9.

Varley, M. I., Beven, K. I. and Oliver, H. R., 1996. Modelling solar radiation in steeply sloping terrain. International Journal of Climatology, 16: 93-104.

Varnes, D. J., 1978. Slope movement types and processes. In: Landslide Analysis and National Academy of Sciences. Special Report 176, p.11-33.

Warren, P. S., and Hume, G. S., 1939. Geological Map of Hardisty; Scale 1: 253,440. Department of Mines and Resources, Geological Survey of Canada.

Watry, S. M., Ehlig, and P. L., 1995. Effect of test method and the procedure on measurements of residual shear strength of bentonite from the Portuguese Bend landslide incidence. In: Clay and shale slope instability. Edited by W. C Haneberg and S. A. Anderson. Geological Society of America, Review in Engineering Geology, Volume X.

Wilkinson, L., 1990. SYSTAT: The system for statistics. Evanston, IL, SYSTAT, Inc.

Williams, G. D., and Burk, C. F., 1964. Upper Cretaceous. In: Geological History of Western Canada. Edited by R. G. McRossan and R. P. Glaister. Alberta Society of Petroleum Geologists. Calgary, AB, p.169-190.

Wilson, R. G., 1970. Topographic influences on a forest microclimate. Climatological research series No. 5. McGill University, Montreal.

Wolfe, J. N., Wareham, R. J., and Scofield, H. J., 1943. The microclimate of a small valley in central Ohio. Transactions of the American Geophysical Union, 24: 154-66.

Yoon, T. N., 1974. Rochester area, geology and groundwater availability. Alberta Environment Earth Sciences and Licensing Division.

Zaruba, Q., and Mencl, V., 1969. Corrective measures. Landslides and their control. Czechoslovak Academy of Sciences. Prague.

Zaruba, Q., and Mencl, V., 1982. Landslides and their control. Elsevier, Amsterdam.

Zoltai, S. C., and Vitt, D. H., 1990. Holocene climatic change and the distribution of peatlands in western interior Canada. Quaternary Research, 33: 231-240.

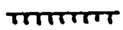
APPENDIX A

AIRPHOTO OVERLAYS ON THE BATTLE RIVER IN THE BEARPAW FORMATION

From A1 to A6

Airphoto Line No.: 9, 10, 11
AS 3026, 3027

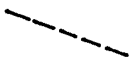
LEGENDS OF AIRPHOTO OVERLAYS IN APPENDICES A, B AND C*


SCARP, length of downslope lines give an indication of length of slope, line marks top of feature


BREAKS OF SLOPE, convex


BREAKS OF SLOPE, concave

GEOLOGICAL BOUNDARY, certain and approximate


MEASUREMENT LINE, with measurement numbers

FORM LINE, raised feature


RIVER, STREAM with direction of flow


RIVER TERRACE, unspecified type

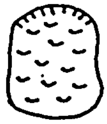

SURFACE SLOPE, straight and uniform


RIVER CHANNEL with the direction of flow

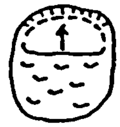
F - Fluvial deposit, including $\frac{Ft}{R}, Ft$

C – Colluvial deposit, including C_f, Cv or $\frac{C_f}{R}, \frac{C_v}{R}$

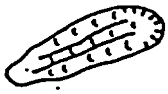
* Legends adopted from Dearman and Fookes (1974), and Cruden and Thomson (1987)



LANDSLIDE, type undetermined

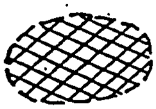


COMPOUND LANDSLIDE, with backtilt of displaced mass



FLOW SLIDE

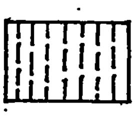
GRAVEL PIT



EXCAVATION

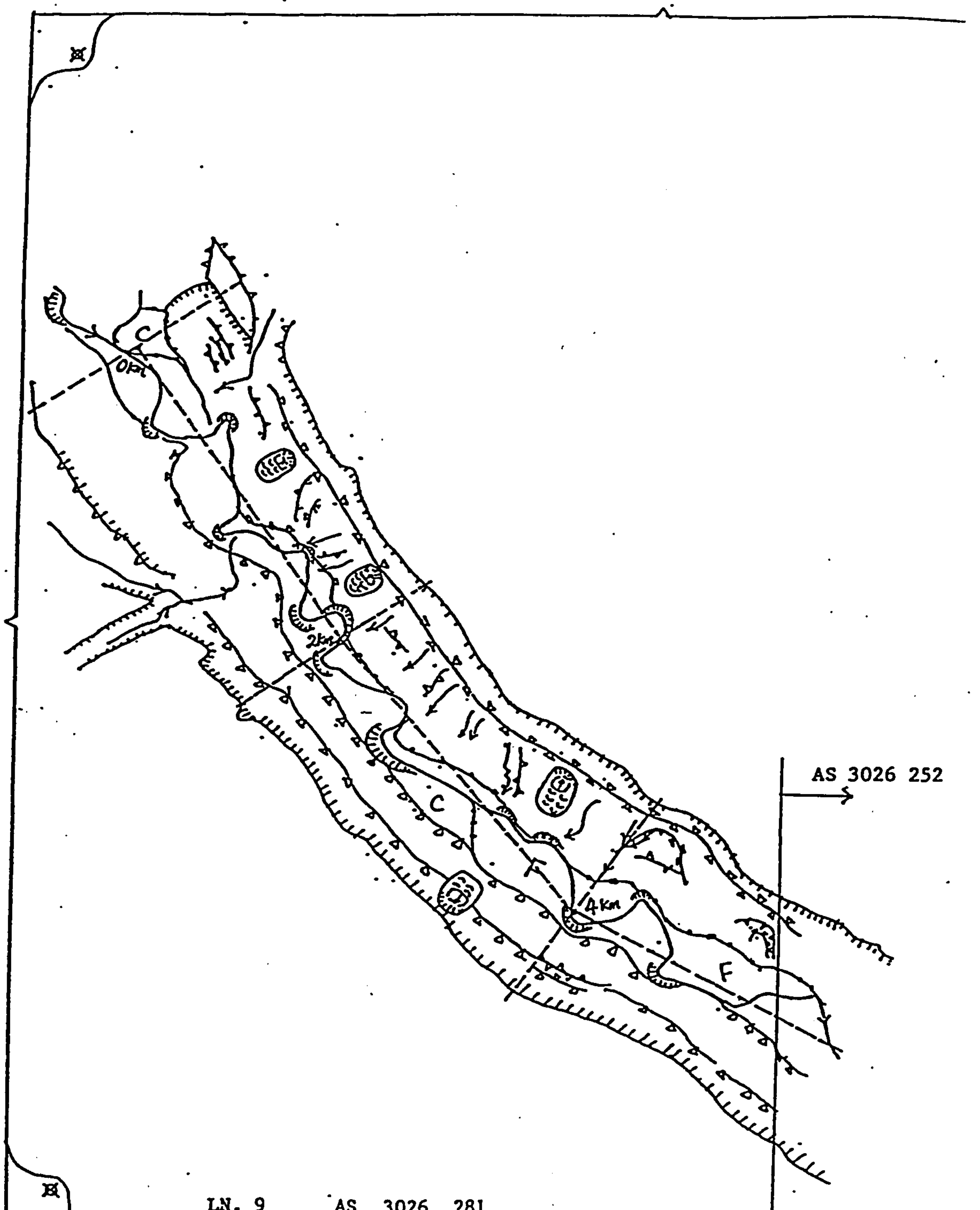
LAKE or POND

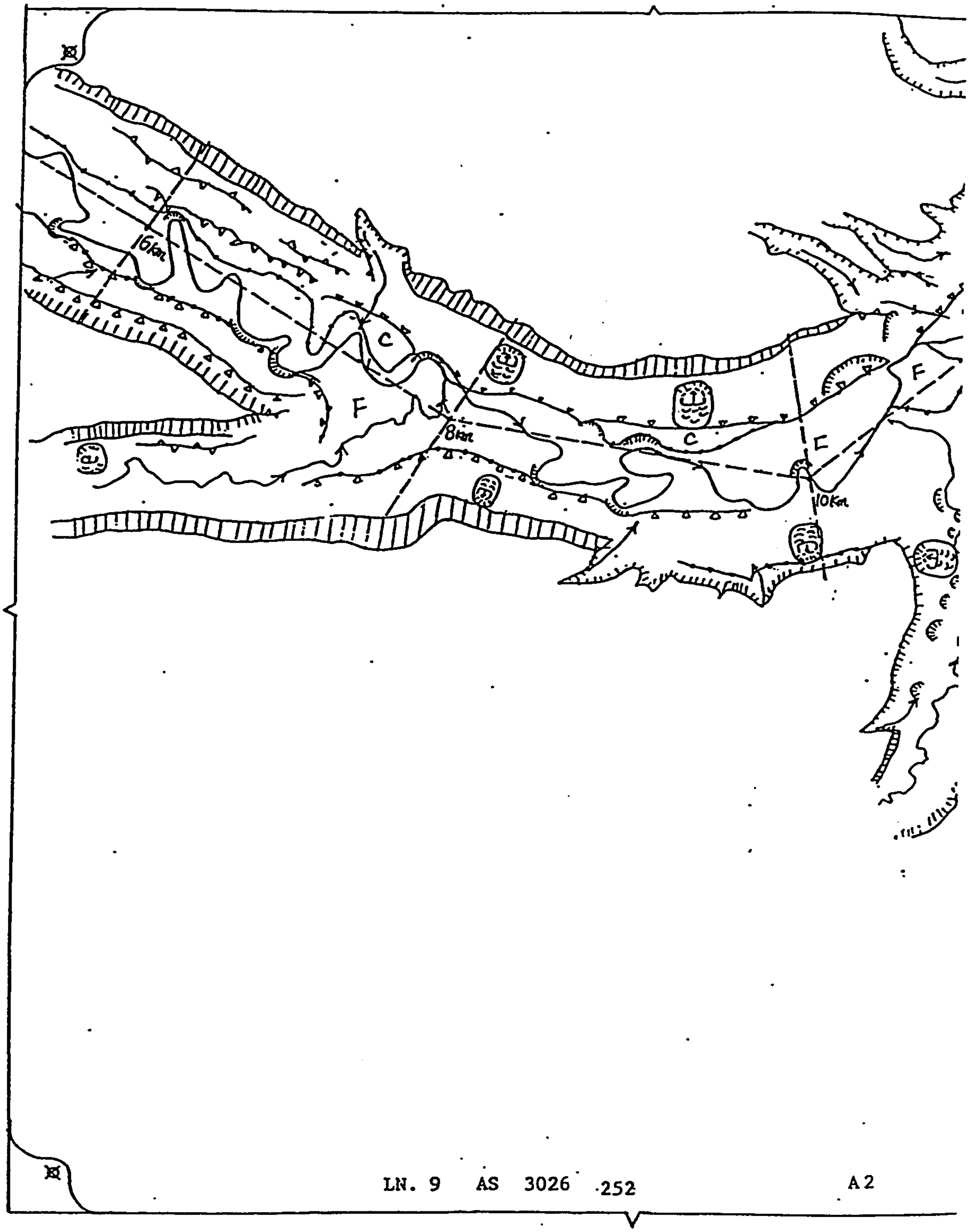
BOUNDARY of landslides**



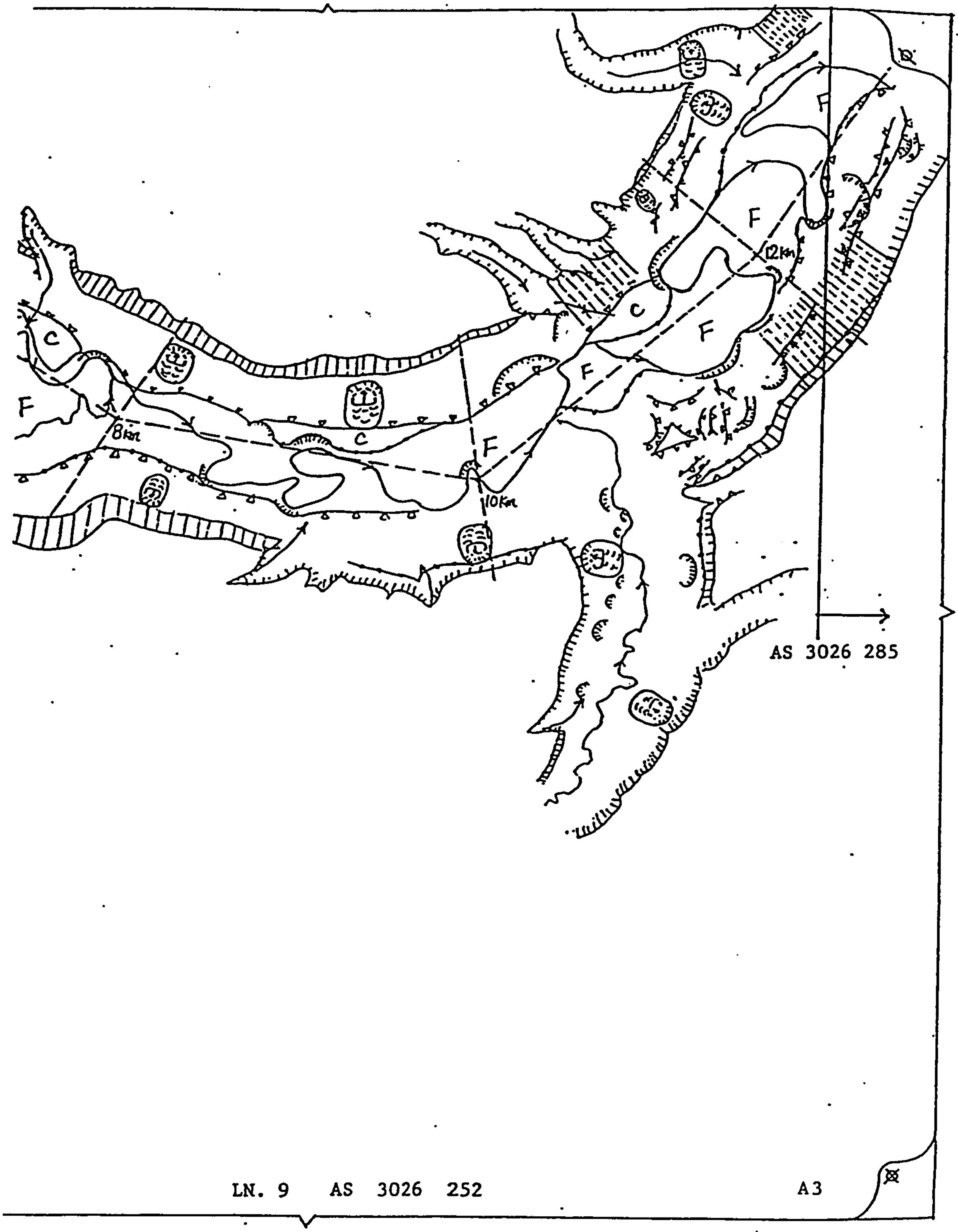
NONLANDSLID section (only for Appendix A)**

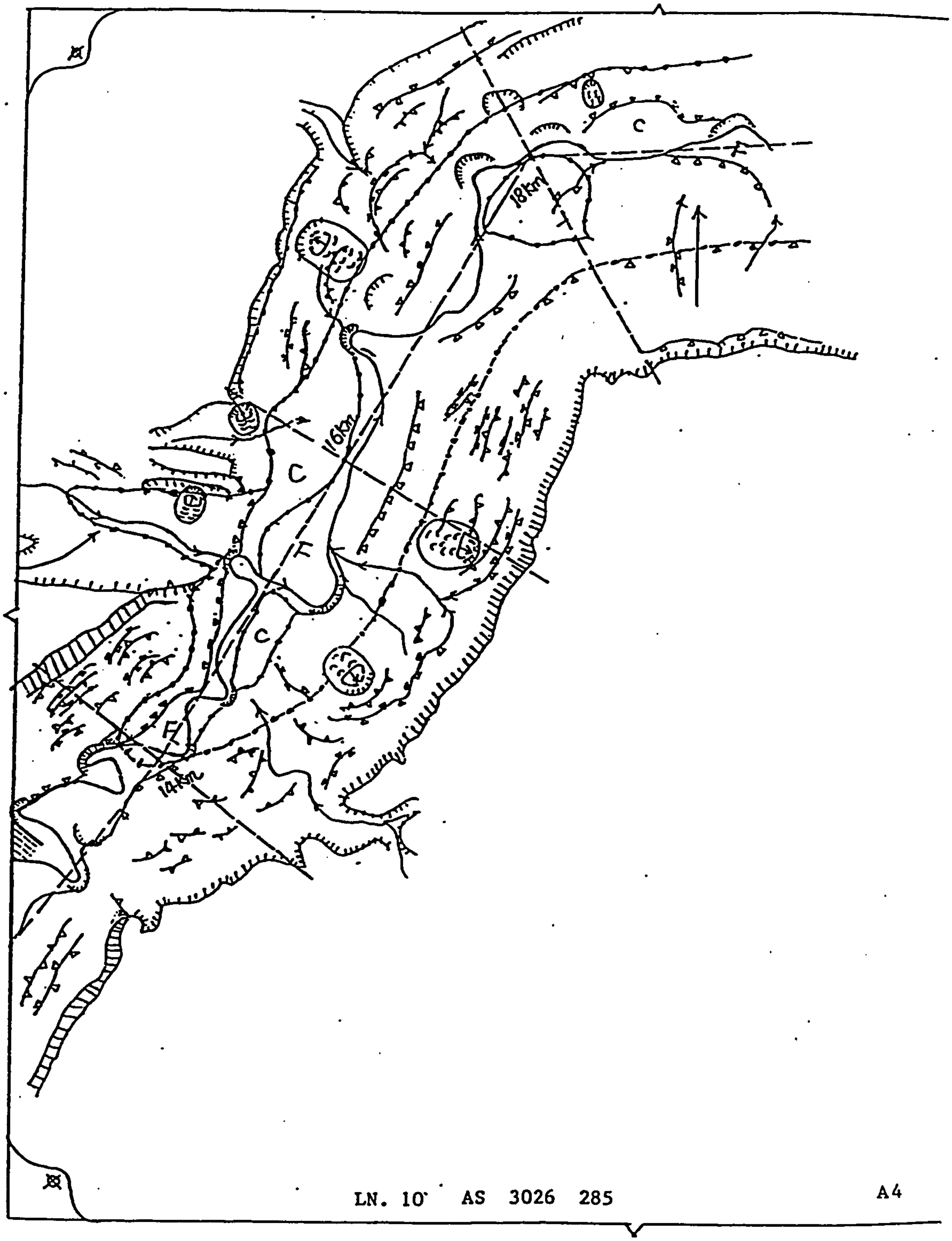
** Legends are not in Dearman and Fookes (1974), and Cruden and Thomson (1987)


AS 3026 252
LN. 9
AS 3026 281
A1

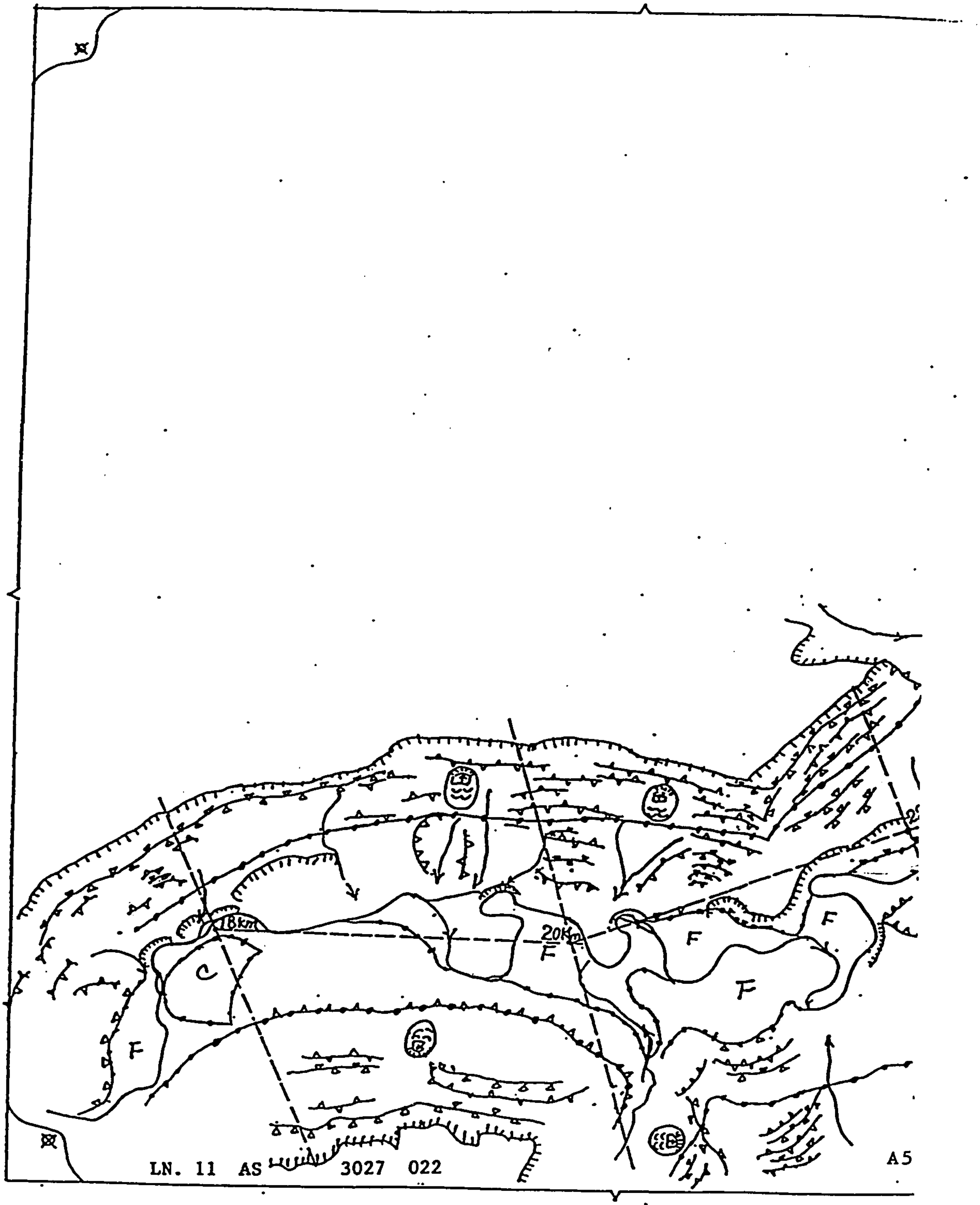


16km
C
F
8km
C
C
F
10km
LN. 9 AS 3026 252
A2

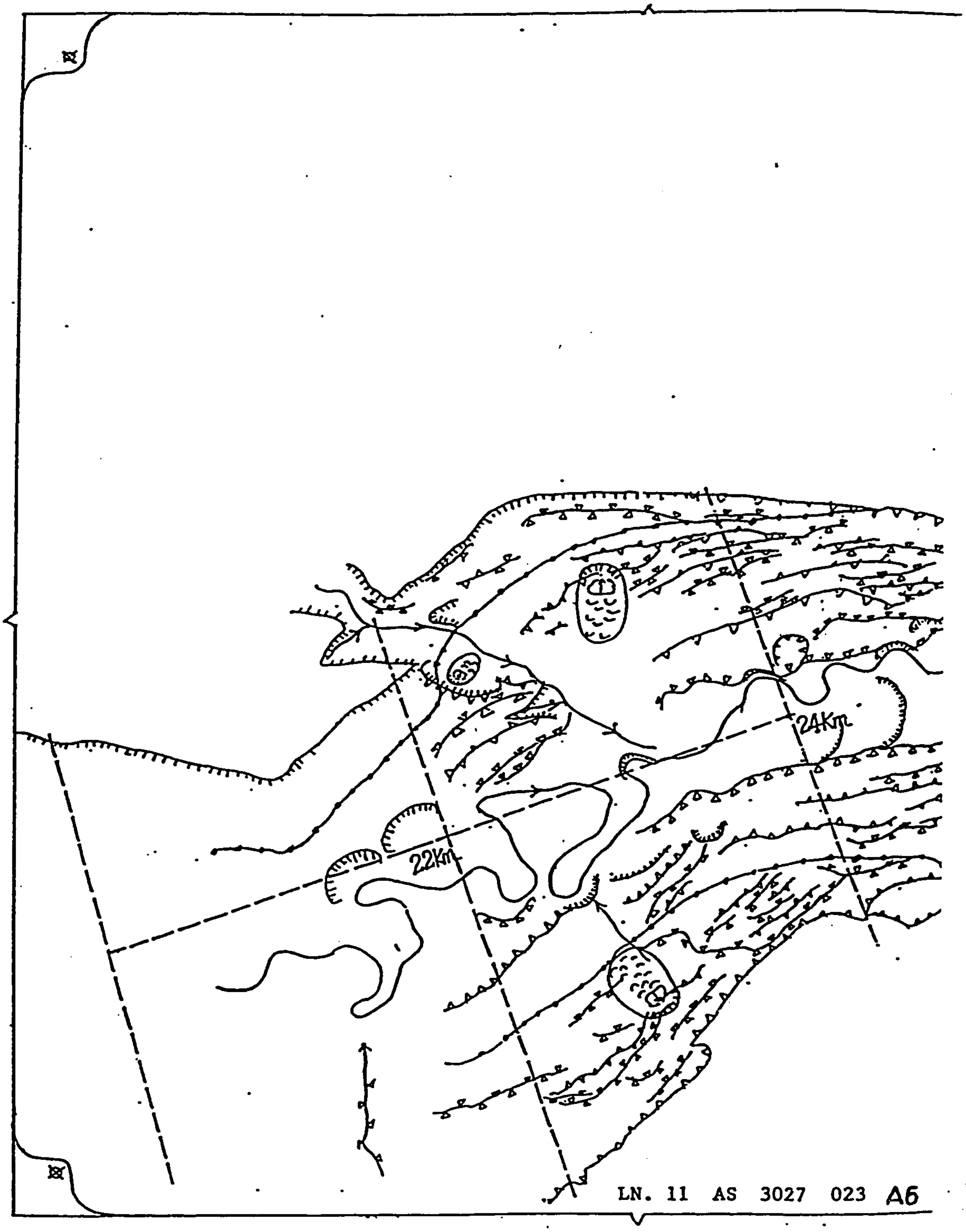

C
F
C
F
C
F
F
F
F
8km
10Km
12Km
AS 3026 285
LN. 9 AS 3026 252
A3



LN. 10 AS 3026 285 A4



18km
20Km
C
F
F
F
F
LN. 11 AS
3027 022
A5



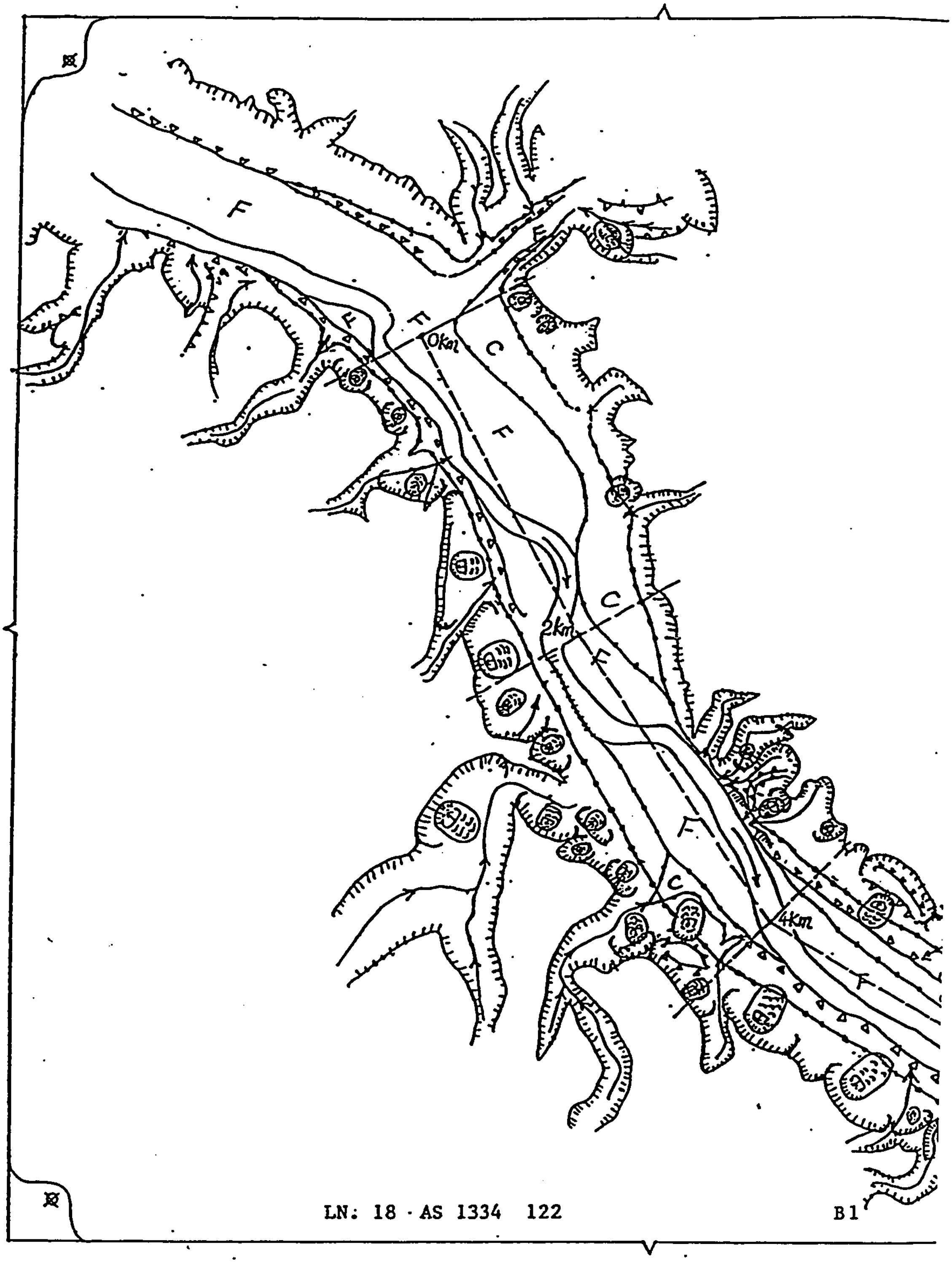
24Km
22Km
LN. 11 AS 3027 023 A6

APPENDIX B

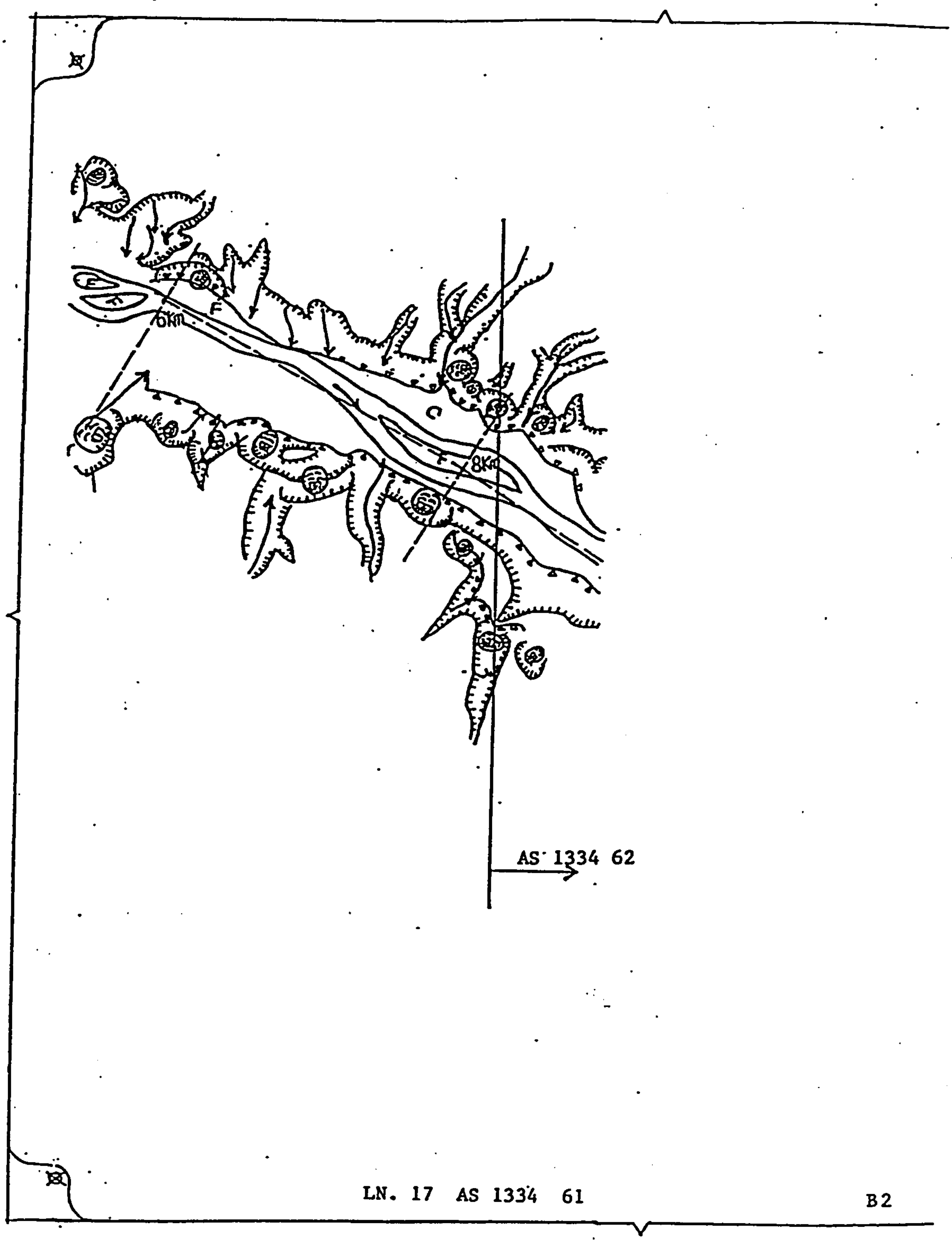
AIRPHOTO OVERLAYS ON THE RED DEER RIVER
IN THE BEARPAW FORMATION

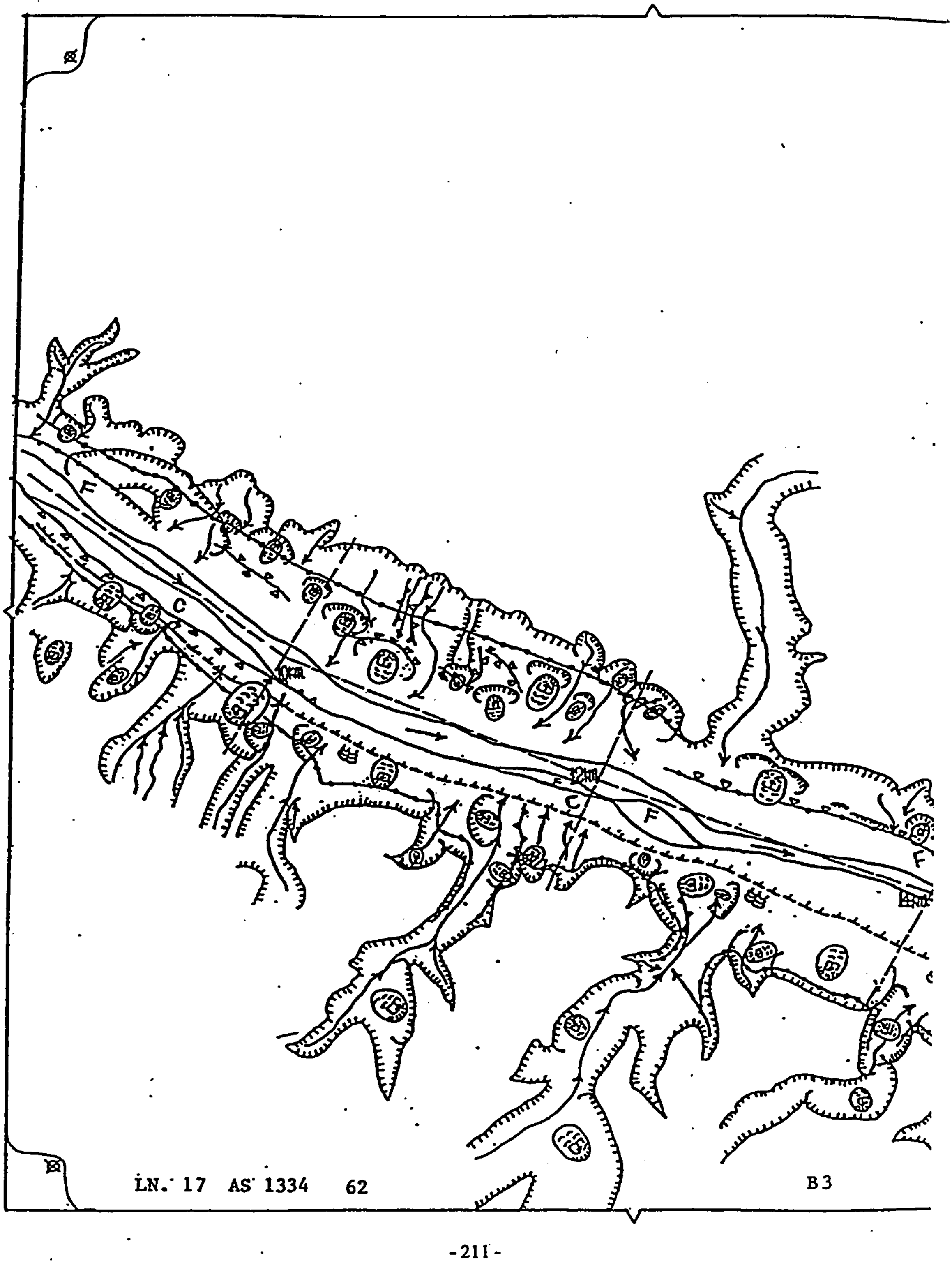
From B1 to B11

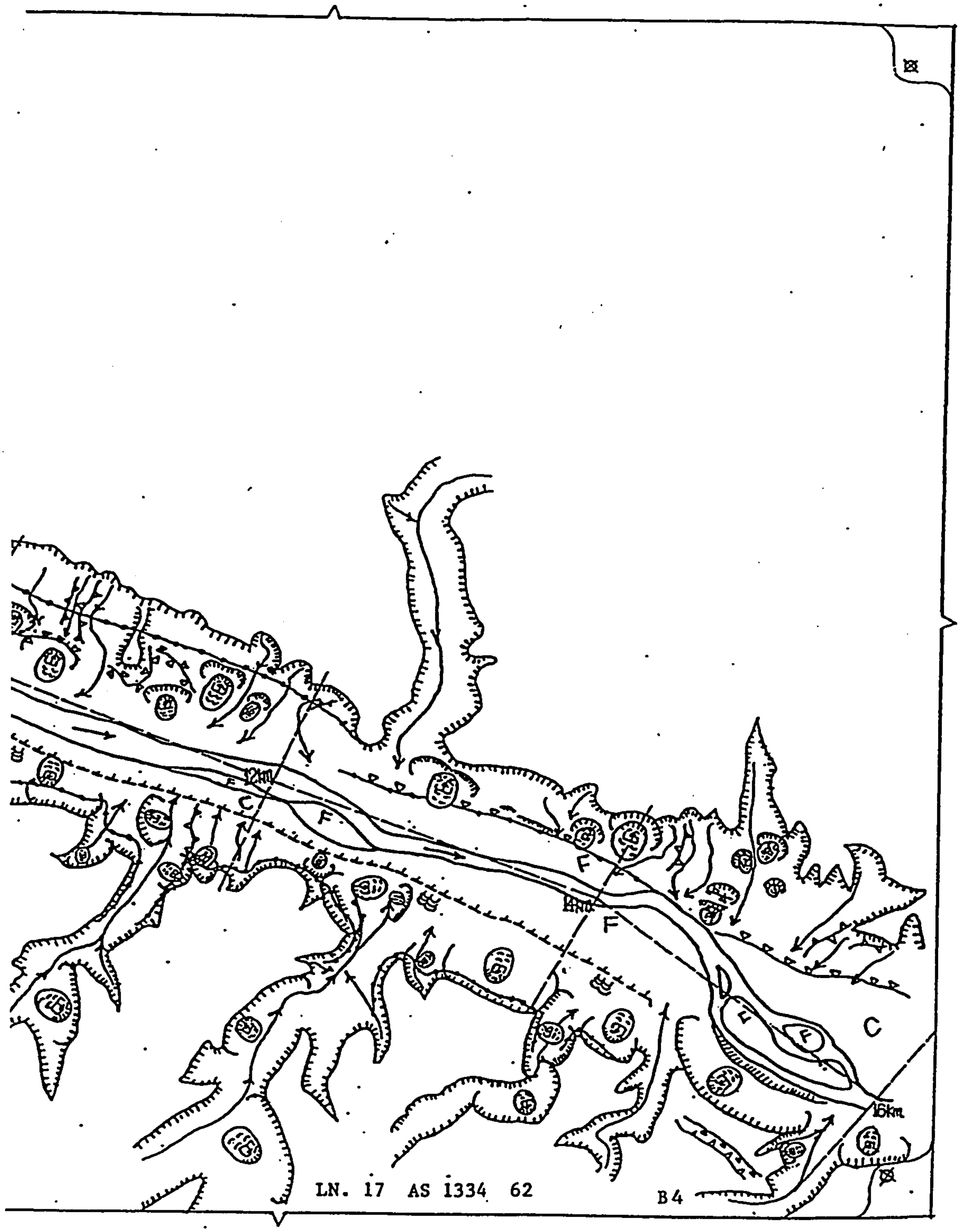
Airphoto Line No.: 10—18
AS 1333, 1334



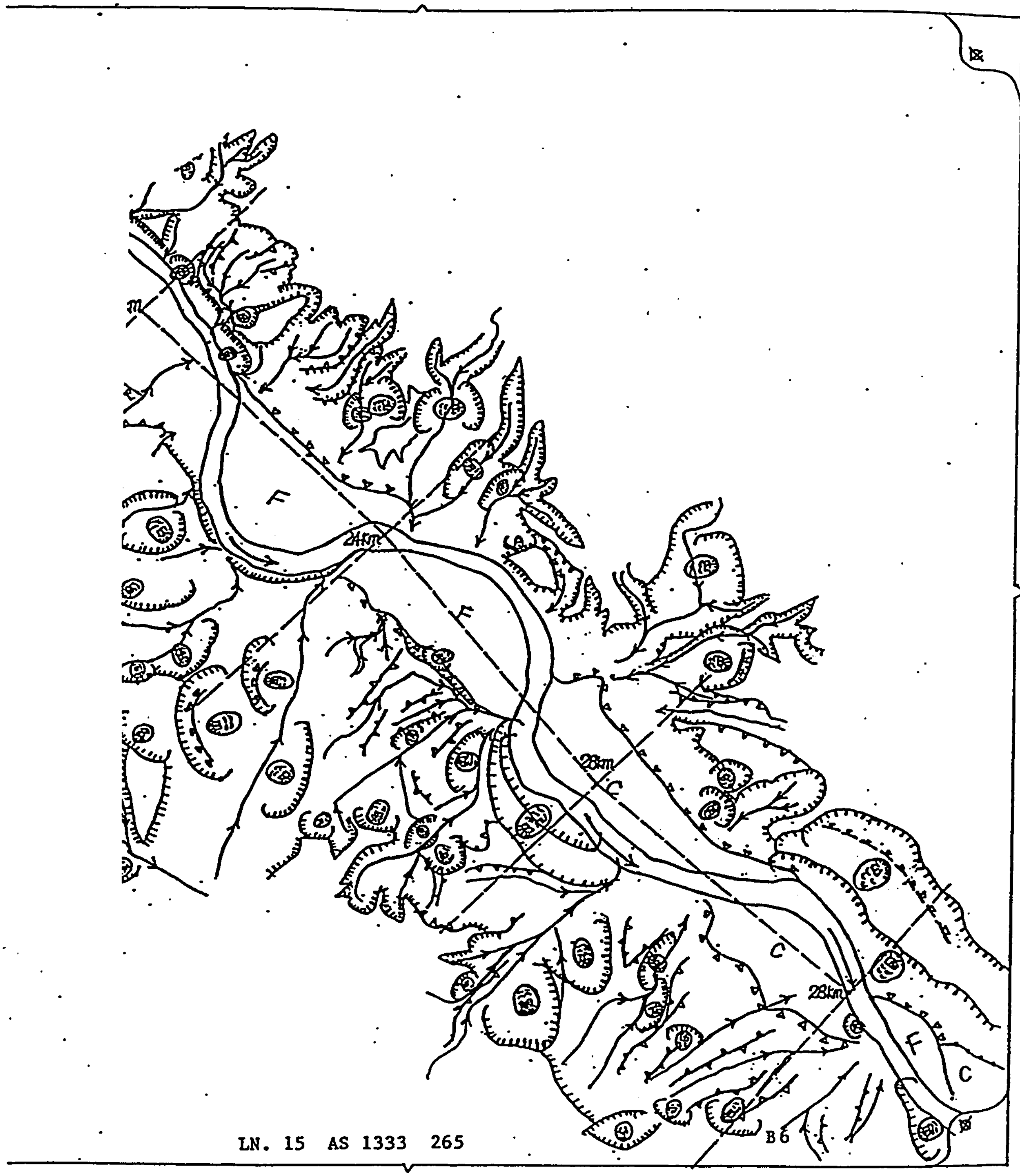
LN: 18 · AS 1334 122 B1


AS 1334 62
LN. 17 AS 1334 61
B2

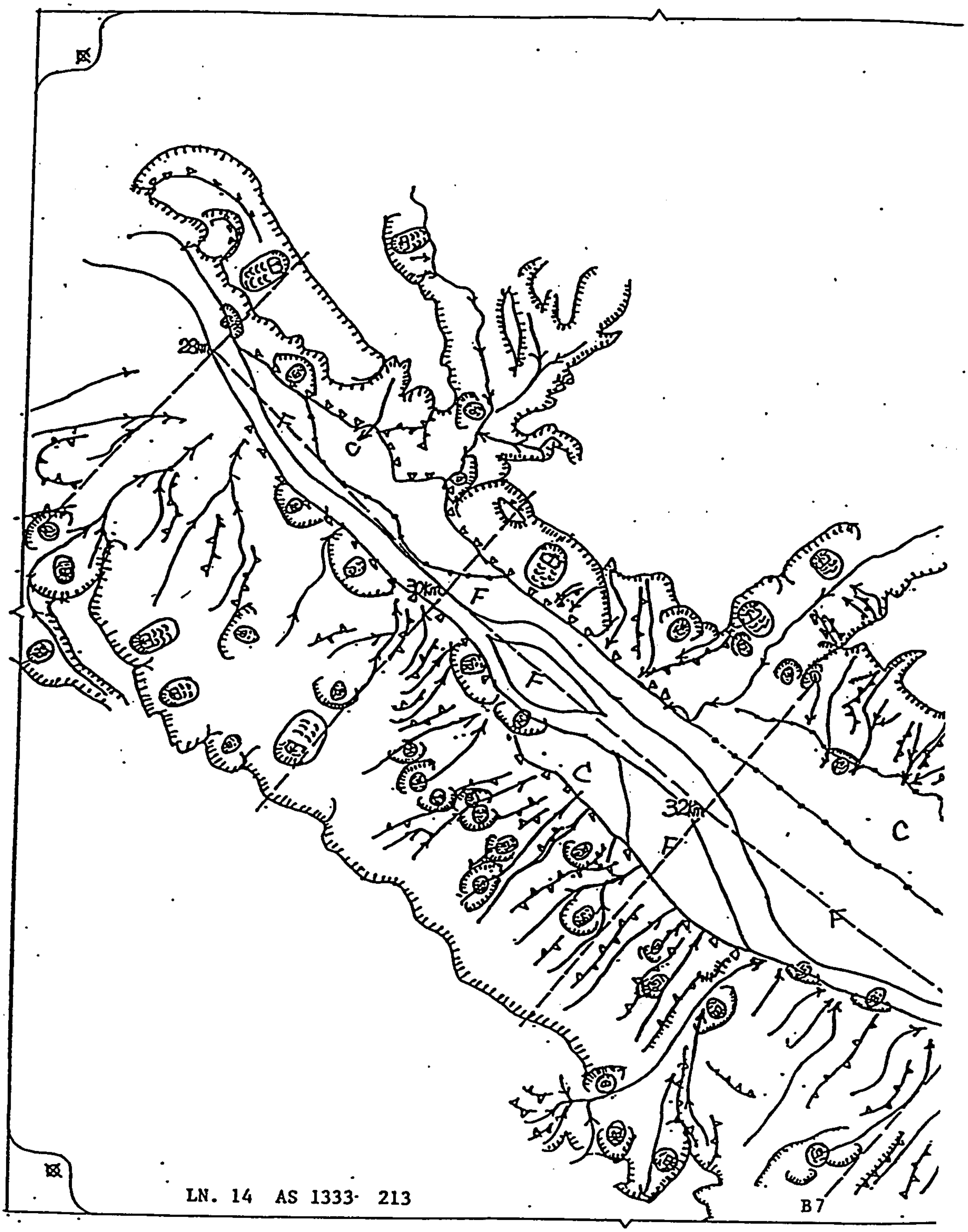

F
C
F
C
F
F
LN. 17 AS 1334 62
B3

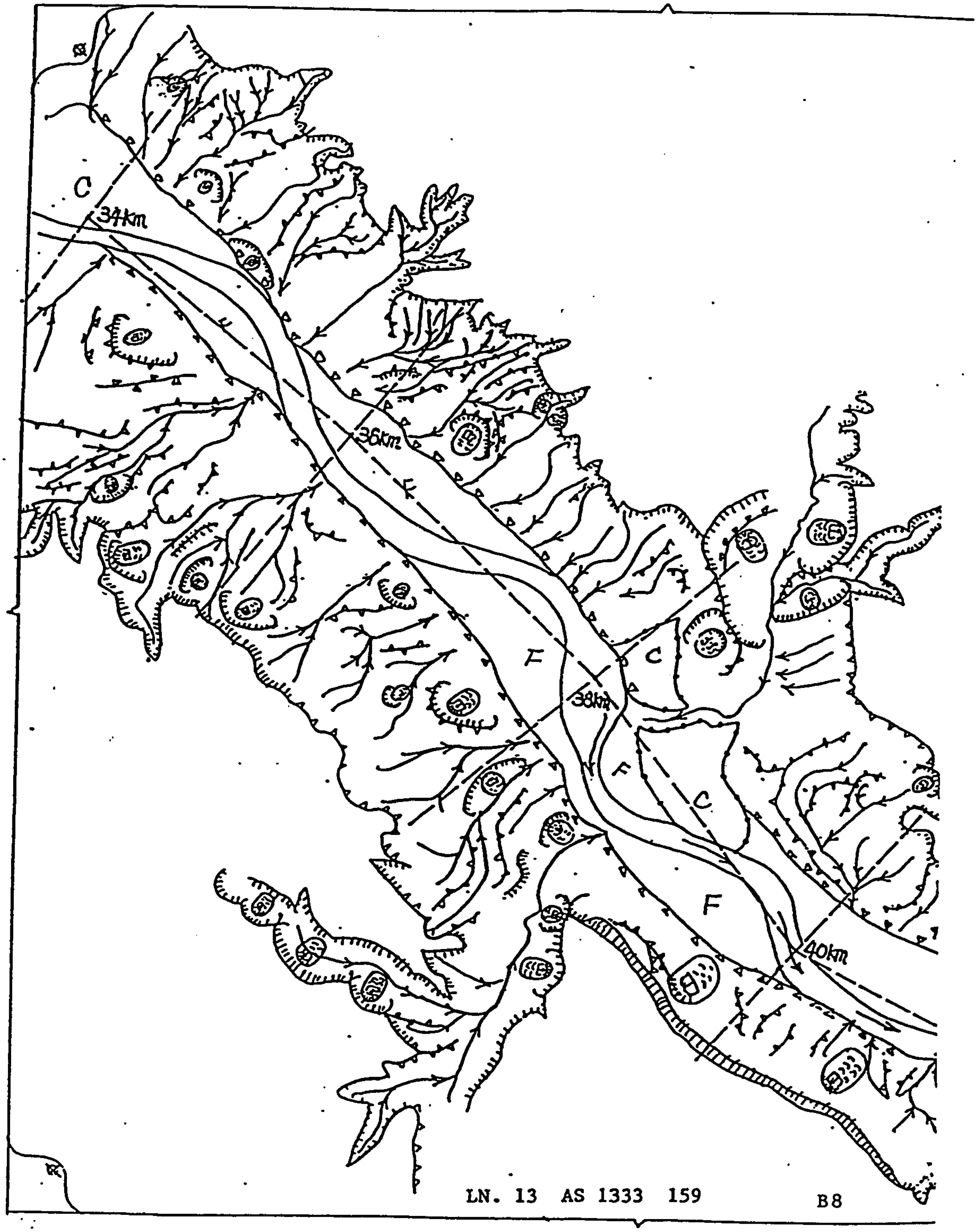

12km
16km
15km
F
C
LN. 17 AS 1334 62
B4

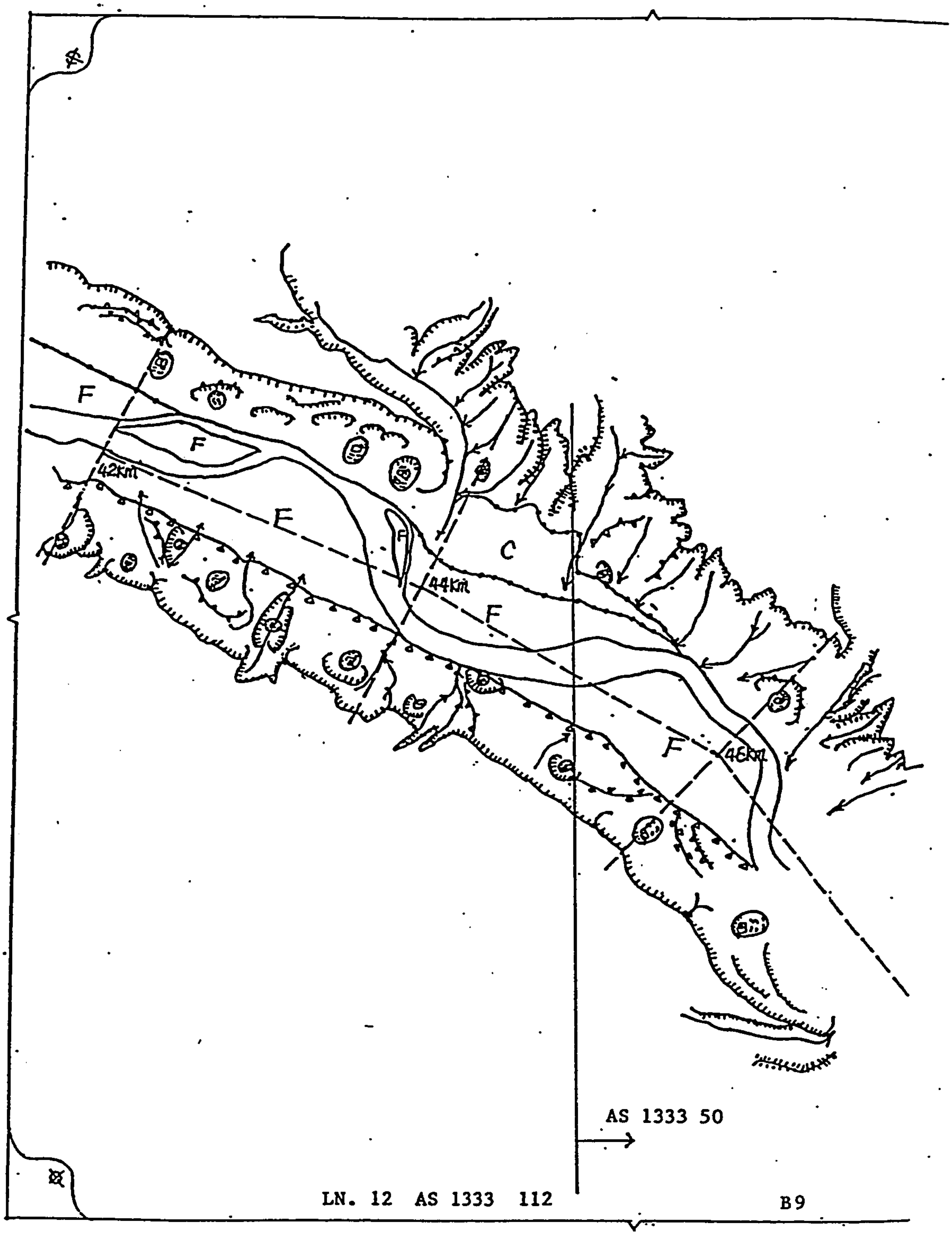

C
16km
C
18km
F
C
20km
LN. 16 AS 1334 3
B5

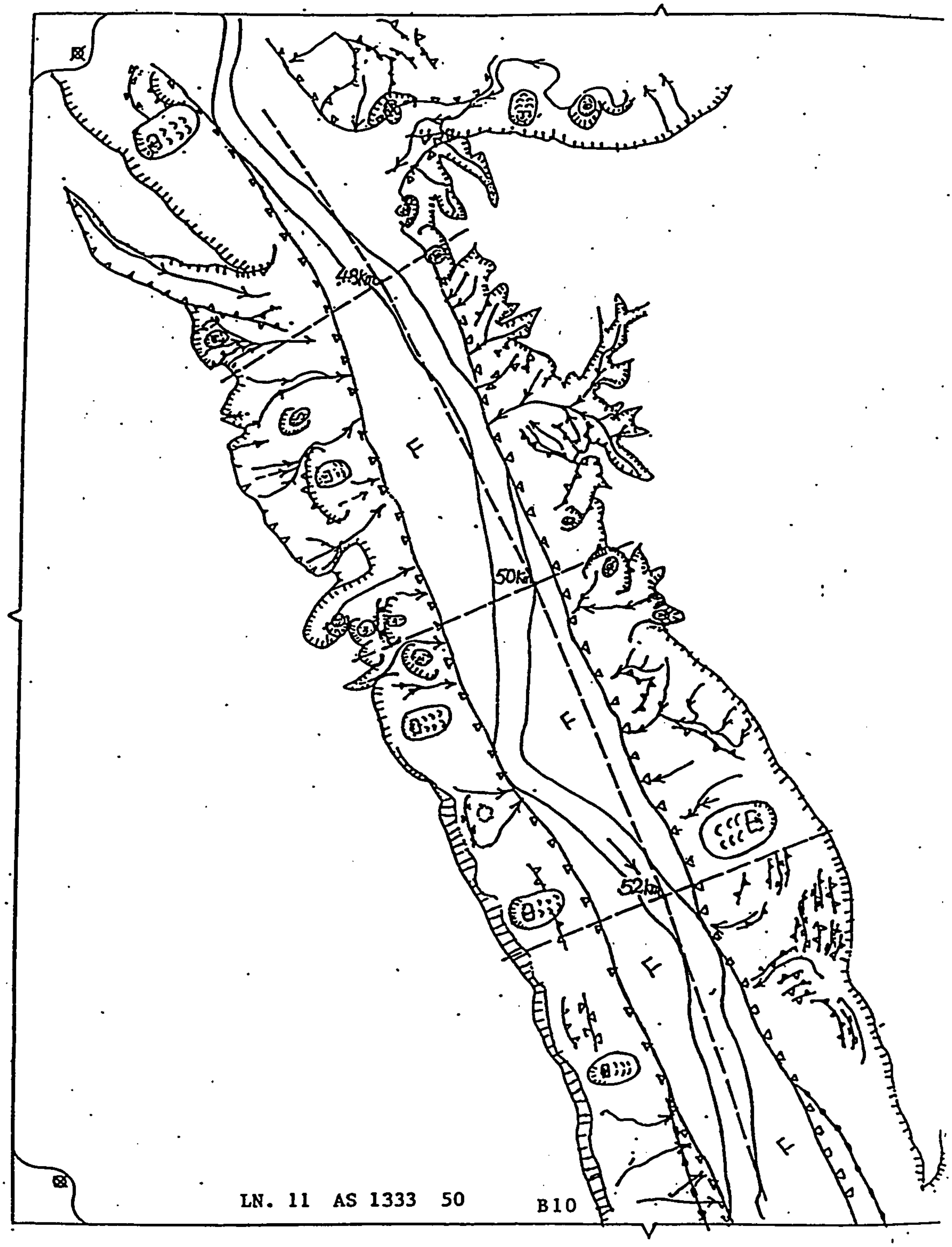


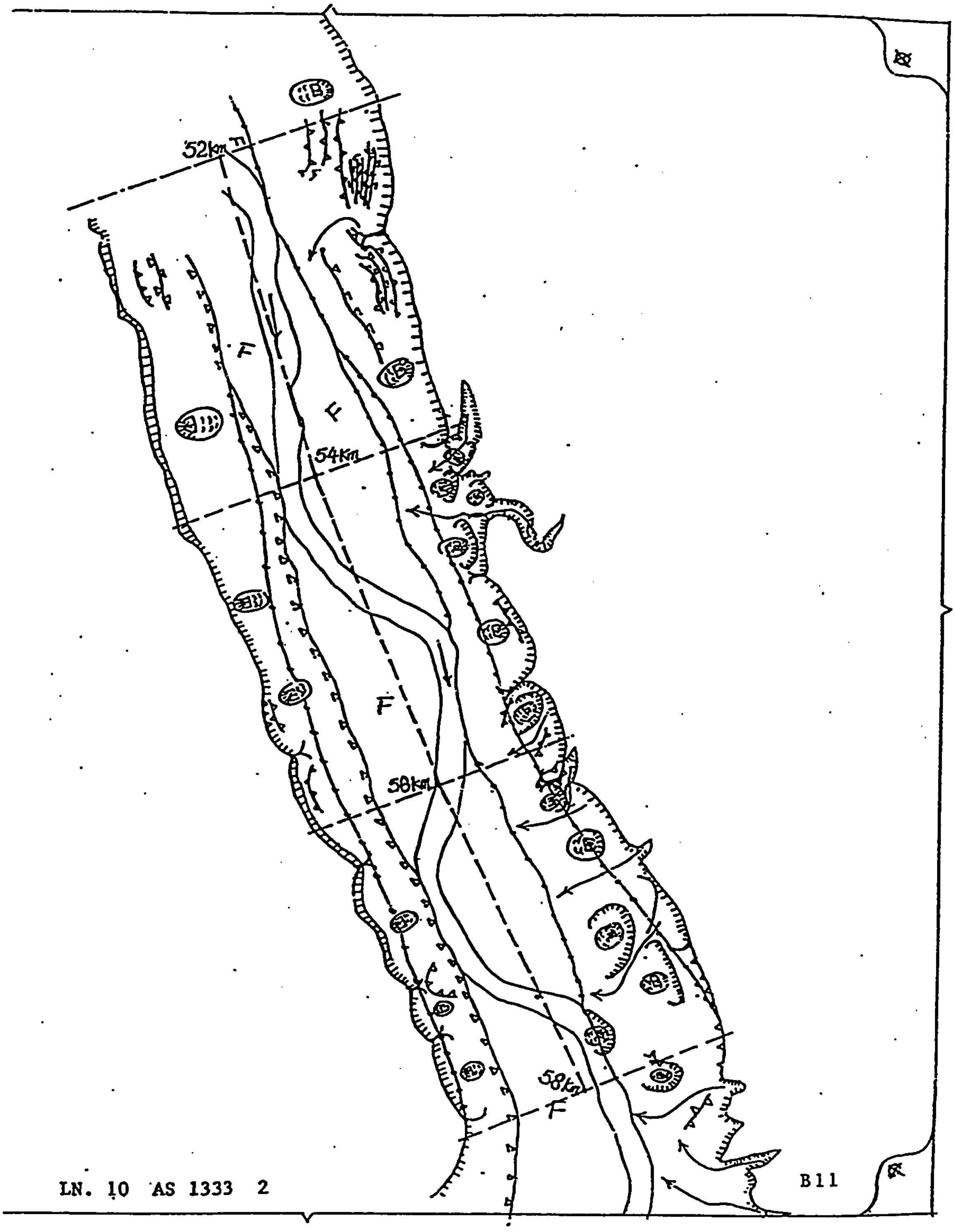
LN. 15 AS 1333 265


28km
30km
32km
F
F
F
C
C
C
A
A
LN. 14 AS 1333- 213
B7


C
34km
36km
F
C
38km
F
C
F
40km
LN. 13 AS 1333 159
B8


F
F
42km
E
C
44km
F
F
46km
AS 1333 50
LN. 12 AS 1333 112
B9


48km
50km
52km
LN. 11 AS 1333 50
B10


52km
54km
58km
58km
F
F
F
F
LN. 10 AS 1333 2
B11

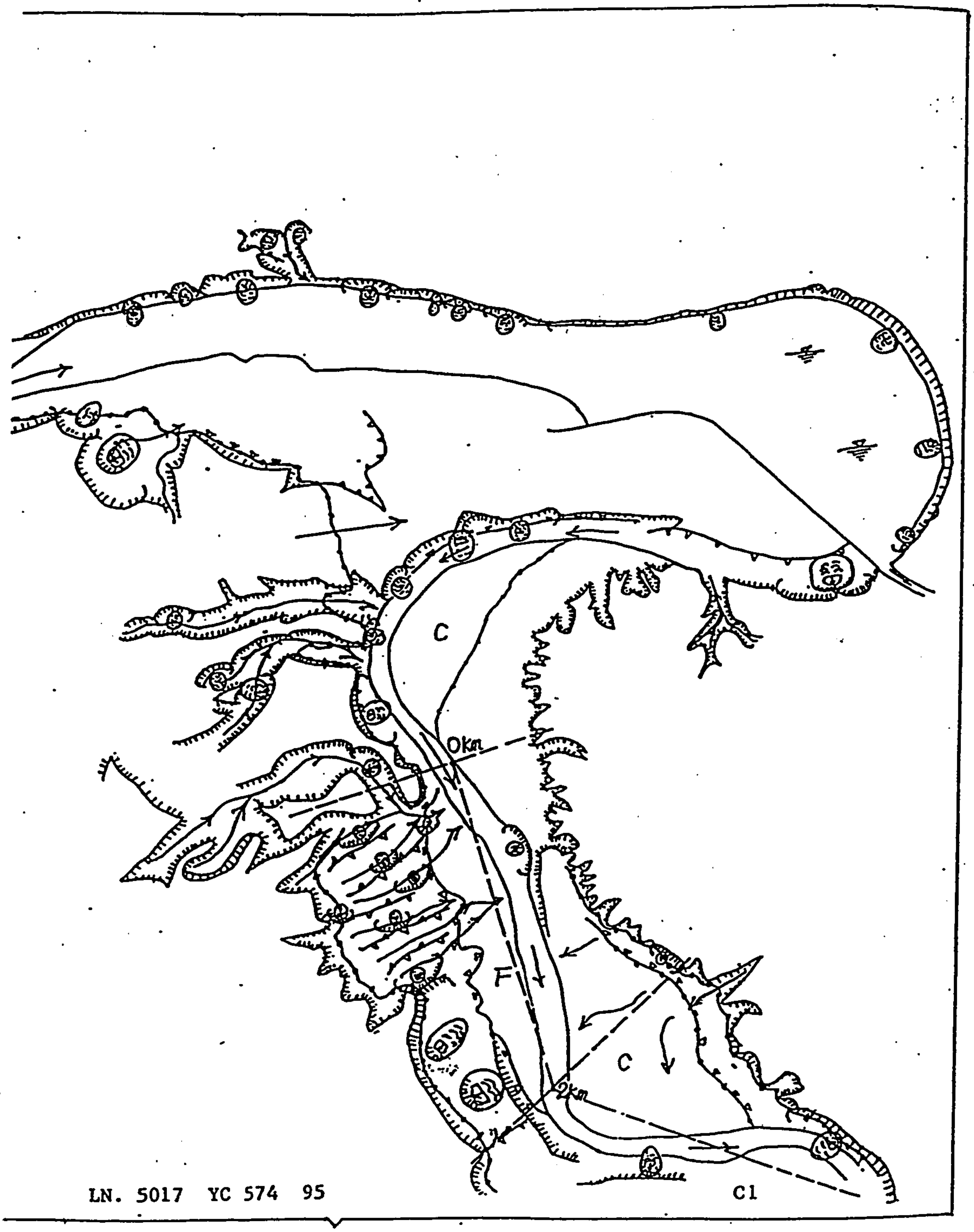
APPENDIX C

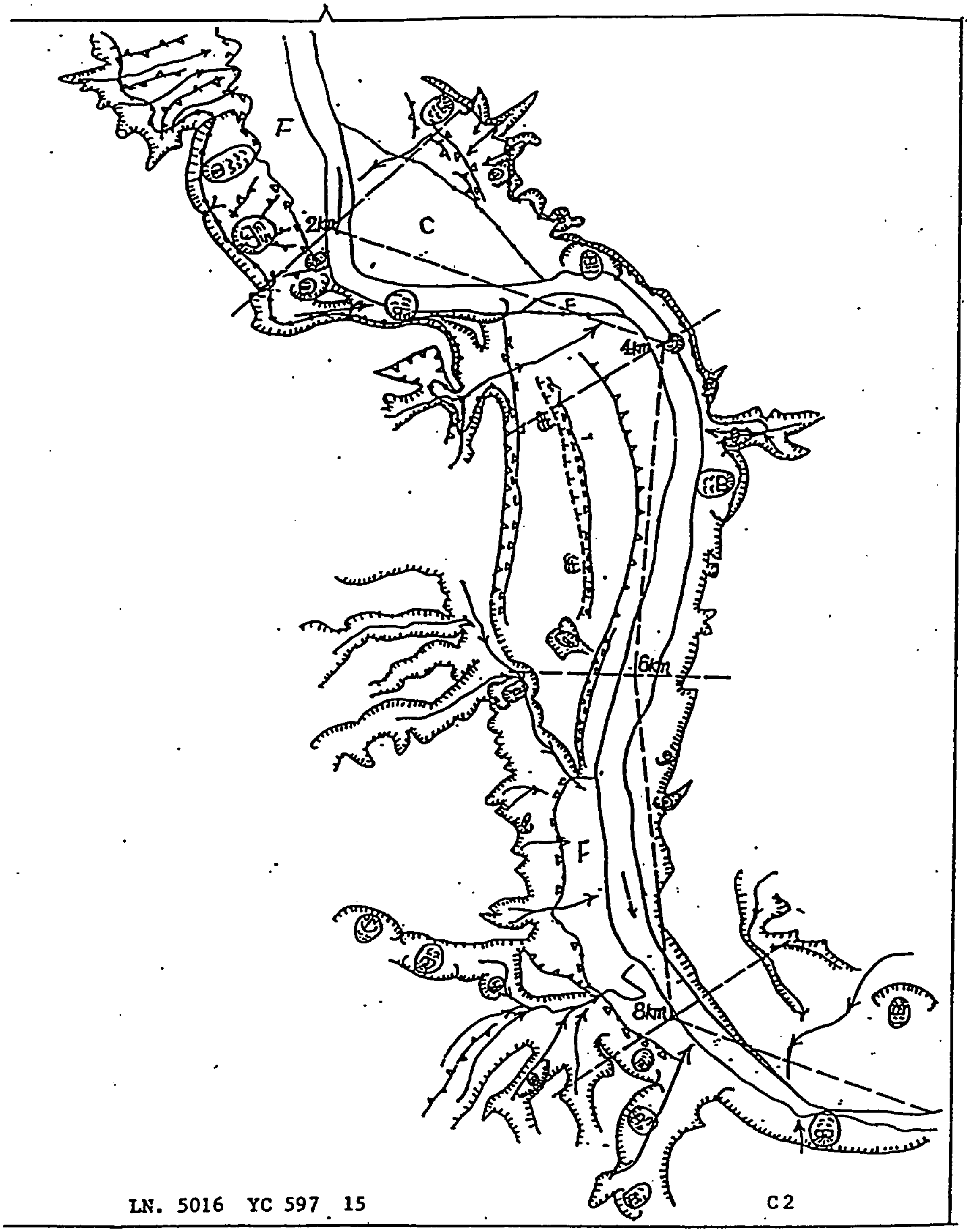
AIRPHOTO OVERLAYS ON THE BOW RIVER IN THE BEARPAW FORMATION

From C1 to C9

Airphoto Line No.: 5010-5017

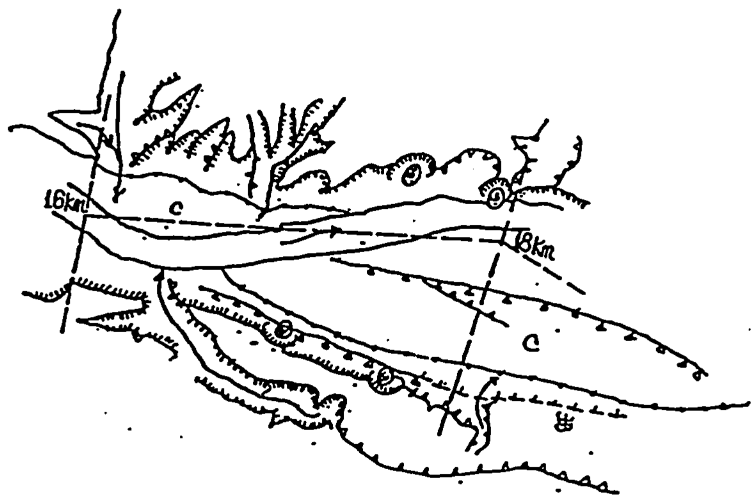
YC 539, 562, 570, 574, 597, 586,


C
OKm
F
C
OKm
LN. 5017 YC 574 95
C1

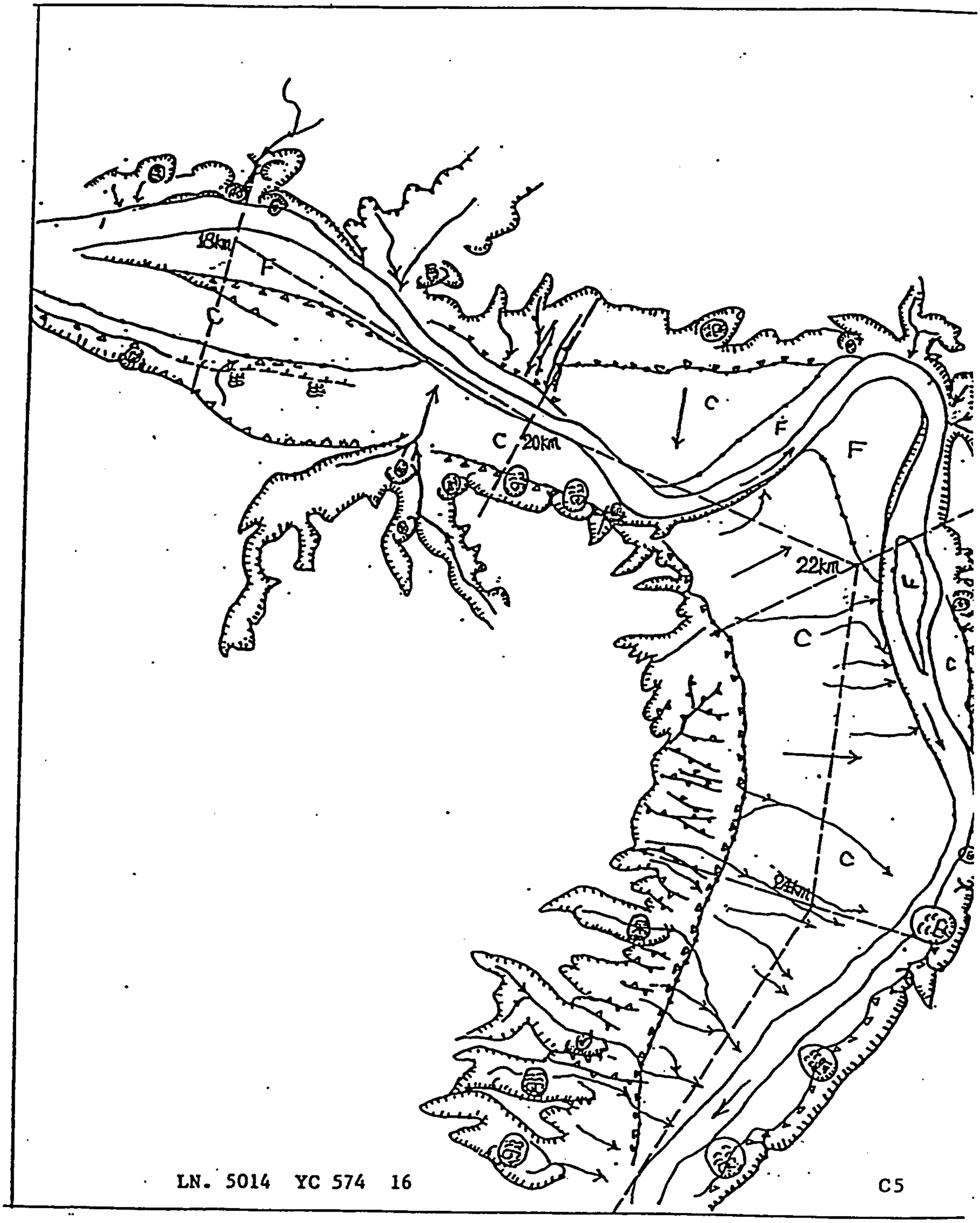

F
C
2km
4km
6km
F
8km
LN. 5016 YC 597 15
C2

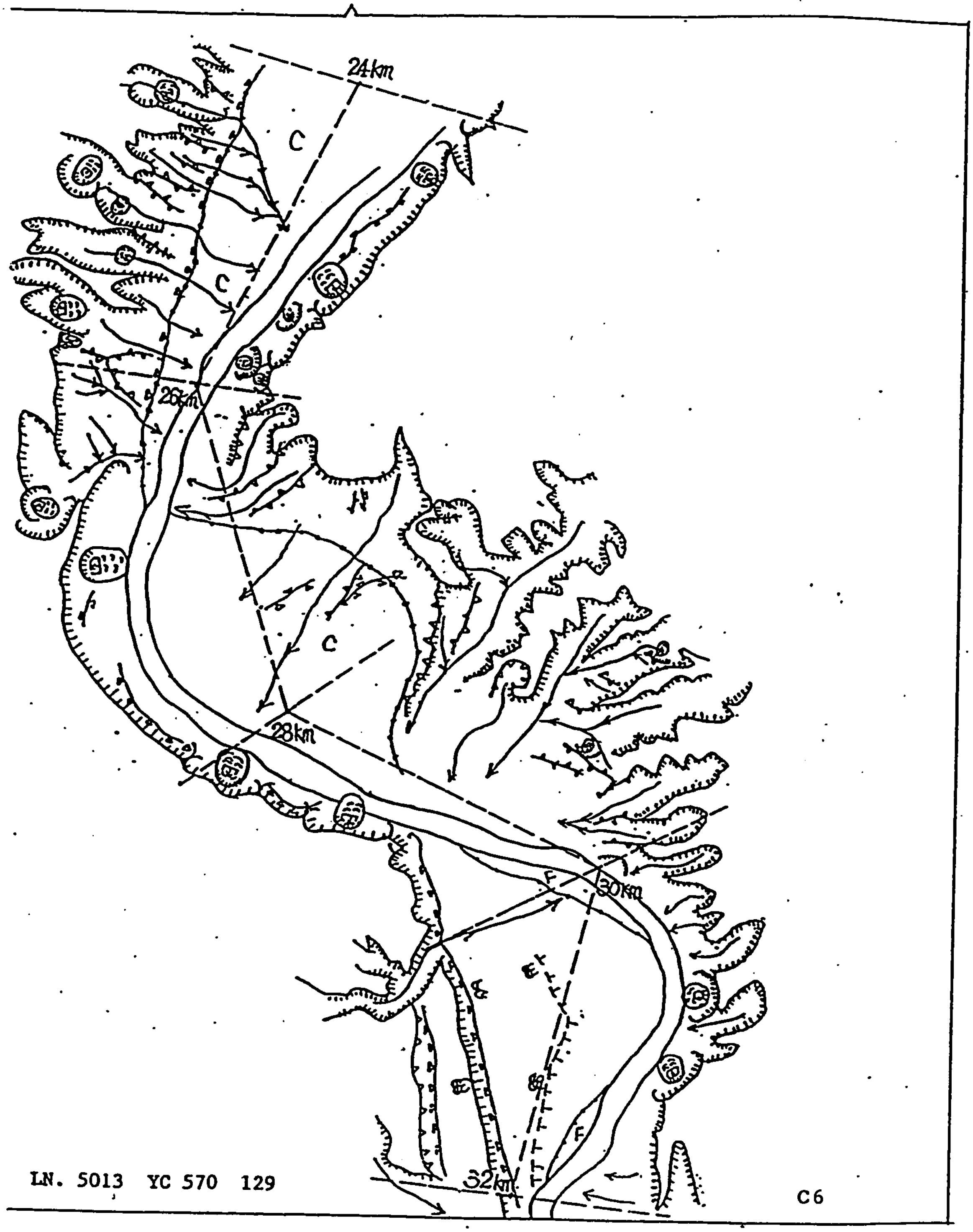
LN. 5015 YC 574 47

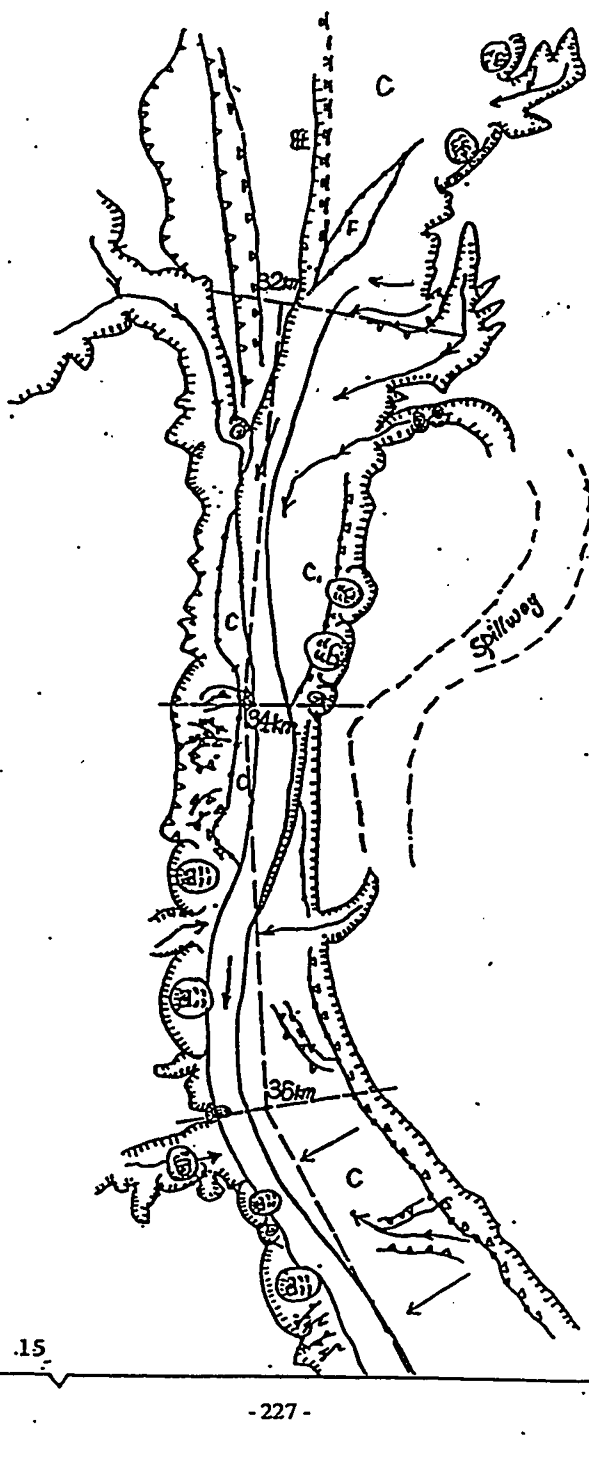
C3



LN. 5014 YC 574 15 C4

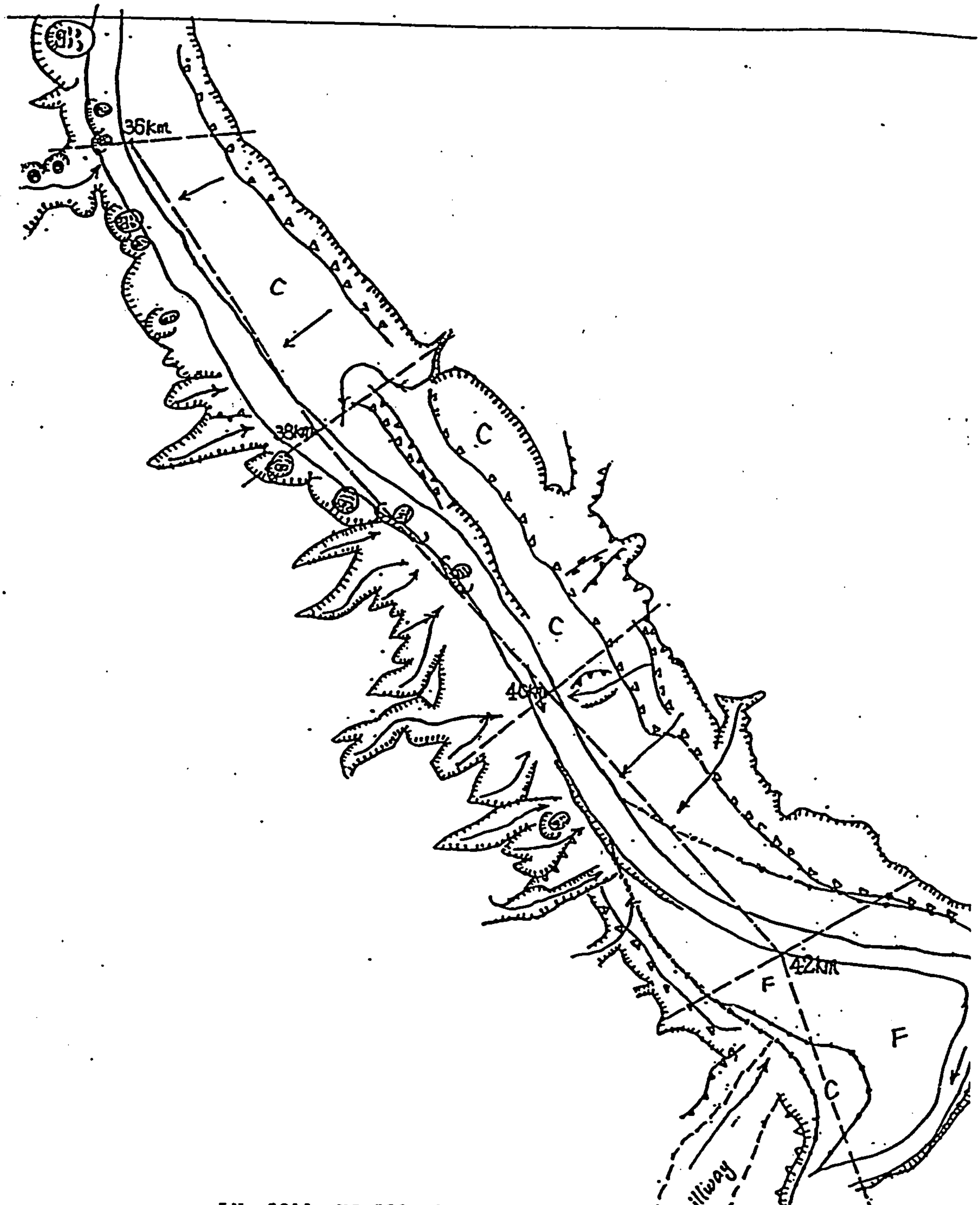

18km
F
C
20km
22km
24km
LN. 5014 YC 574 16
C5


24km
C
C
26km
C
28km
30km
F
F
32km
LN. 5013 YC 570 129
C6



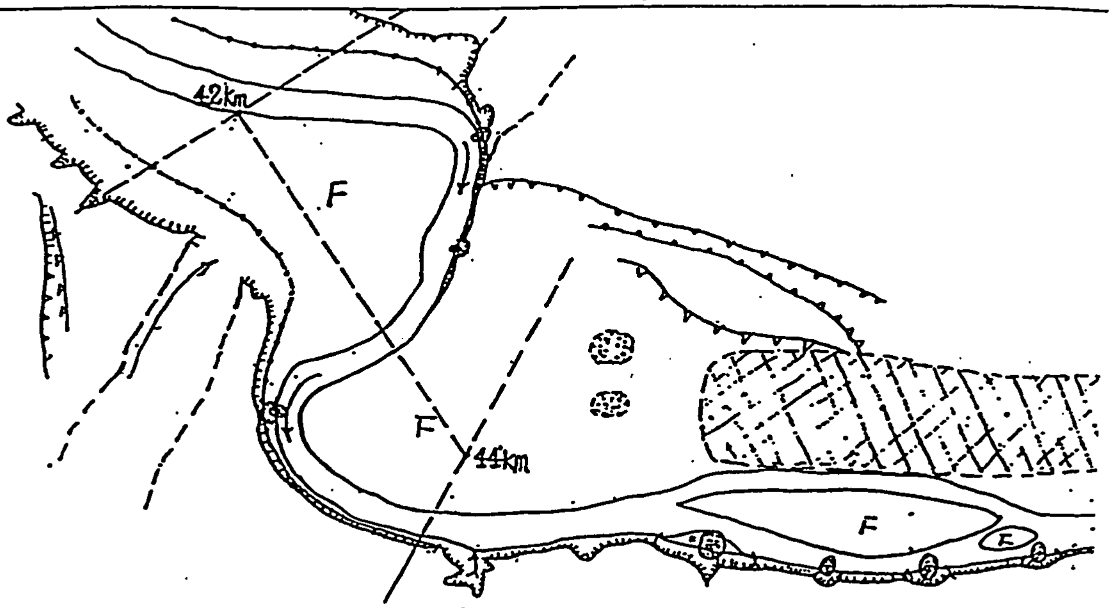
LN. 5012 YC 586 .15

C7



LN. 5011 YC 539 47

C8



LN. 5010 YC 562 51 C9