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**THE GEOMORPHOLOGY OF THE CAMPBELL UPLIFT,
NORTHWEST TERRITORIES, CANADA**

by

MICHAELLA McGUINNESS, B.Sc.

**A thesis submitted to the Faculty of Graduate Studies
in partial fulfillment of the requirements for the degree of**

Master of Arts

**Department of Geography and Environmental Studies
Carleton University**

Ottawa, Ontario

September 1999

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**"THE GEOMORPHOLOGY OF THE CAMPBELL UPLIFT,
NORTHWEST TERRITORIES, CANADA"**

submitted by **Michaela McGuinness, B.Sc. (Hons.)**

in partial fulfillment of the requirements for
the degree of Master of Arts

Chair, Department of Geography and Environmental Studies

Thesis Supervisor

CARLETON UNIVERSITY
September 1999

ABSTRACT

The aims of this study are: to describe the geomorphology of the Campbell Uplift southeast of Inuvik, NWT (Canada); to determine what processes and filters currently operate, and have in the past, to produce the limestone and dolomite terrain; and to present the results in a model of landscape development. The present landforms are hypothesized to have developed due to both karst and periglacial processes acting on an inherited landscape mainly of glacial origin, with these processes expressed principally through the filter of lithological variation. The landforms documented and described include karren, pavements, labyrinth and pinnacle karst, frost shattered and wedged forms, solifluction lobes, glacially plucked and abraded surfaces, glacial grooves, whalebacks, and undercuts. They were analyzed in terms of their relation to lithology (grain size, rock type, and insoluble content). The evidence suggests that lithology is not the only filter of landforms but that sedimentary structures are also important.

ACKNOWLEDGEMENTS

My parents and Matthew were incredible throughout my two years at grad school - thank you and all my love. Maureen, thanks for the 'computer drawing' expertise as well as your concern and good wishes. Thank you to my family (extended included) and friends all over the country for "being there".

Thank you to Dr. Joyce Lundberg for taking me on as a grad student and providing the opportunity for me to go north. Thank you to the MA students for the fun we shared and the moral support you gave by listening and laughing. Thank you to Drs. Chris Burn and David Bennett for helping me through the rough parts. Thank you to Larry Boyle for the technical support. Thank you to Dr. Derek Ford for his timely help and to Hazel Anderson for her continuous encouragement.

The Inuvik Research Centre staff provided a great introduction to the north and helped me get into and out of the field. My field assistants worked hard and special mention to Rachel Sutton for her help and presence. NSTP partially funded my field work for which I am grateful. The Girl Guides of Canada lent me equipment and provided years of outdoor experience which made the field work portion of my thesis fun instead of just hard work.

Finally to everyone who listened endlessly to my stories and complications while sharing many a cup of tea (or coffee or ...) - thank you very much for the support.

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CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

The Campbell Uplift is located southeast of Inuvik, Northwest Territories, Canada. It is within the zone of continuous permafrost and is composed of carbonate bedrock. Several years ago Dr. Joyce Lundberg made a reconnaissance trip to the northeast part of the Campbell Uplift and observed both karst and periglacial landforms as well as evidence that the area had been glaciated. Frost debris obscured some karst features suggesting that they were relict, but evidence of active dissolution was present on newly frost shattered pieces of rock. From these observations, Lundberg hypothesized that both karst and periglacial processes are presently active in the landscape of the Campbell Uplift (Pers. Comm., 1997) and it was decided that more research should be conducted in the area.

This report builds on the preliminary observations by Lundberg. The aim of this research is to document and describe the landforms and lithology of the Campbell Uplift. The descriptions will help determine the processes acting in the study area. During seven weeks of field work, a geomorphological survey of the area was completed. It included the documentation and description of the landforms and lithology of six field areas in the Campbell Uplift. Analysis of these data led to the creation of a landscape development model of the Campbell Uplift.

1.2 INTRODUCTION TO THE STUDY AREA

The 18 km² Campbell Uplift is about 10 km southeast of Inuvik, Northwest Territories, Canada, and is north of the Arctic Circle (Figure 1.1).

Figure 1.1: Campbell Uplift, Northwest Territories, Canada

In contrast to the Mackenzie Delta, to the west, at sea level, the Uplift has an elevation of about 300 feet (90 m) above sea level (ASL) and some areas are as high as 500 feet (150 m) ASL. The study area has many names including the Campbell Uplift, the Campbell Dolomites, and the Campbell Hills. The geomorphology of the area is karst and periglacial with remnant glacial landforms. The geology of the whole Campbell Uplift is Proterozoic argillite, algal dolomite, and quartzite and Cambrian to Devonian marine limestone and dolomite (stipled area, Figure 1.2) (Geology Map 1517A, Aklavik, 1981).

Figure 1.2: Basic geology of the Campbell Uplift, Northwest Territories, Canada (modified from Geology Map 1517A, Aklavik, 1981)

The study areas are located on the Paleozoic (Cambrian to Devonian) dolomite and limestone portion of the Campbell Uplift. There is no distinct boundary between these two rock types although the northern end of the Campbell Uplift is predominantly limestone whereas the southern and western ends are predominantly dolomitic. The area is in close proximity to the Mackenzie Delta; it is sparsely forested and has a subarctic climate. Muskeg and rock outcrops (Figure 1.3) characterize the cliff-bound Campbell Uplift (Figure 1.4).

Figure 1.3: Muskeg and rock outcrops characteristic of the Campbell Uplift

Figure 1.4: Cliffs outlining the east side of the Campbell Uplift with Campbell Lake on the right (east of the Uplift)

1.3 LANDSCAPE DEVELOPMENT MODEL

The landscape development model of the Campbell Uplift, developed during this research, is based on fundamental principles of geomorphology. Geomorphology is "the analysis, systematic description, and understanding of landscapes and the processes that change them" (Bloom, 1998, p.3). This involves the unification of "regional description, reconstruction of geologic history, and the numerical data on chemical and physical processes by which rock masses are altered by water and air" (Bloom, 1998, p.4). W. M. Davis is attributed with organizing geomorphic information under the headings of *structure*, *process*, and *time* (Bloom, 1998, p.4). Structure and process interact through time to shape the earth's landscape. Thus, a geomorphological study of an area answers the questions of how a landscape has developed and changed over time in a certain area as a response to processes and to factors that alter the effect of the processes. It is also thought that the reverse is true, that landform expression can tentatively indicate the processes by which it was formed.

The shape of the earth's surface is affected by numerous natural events, including tectonic, climatological, and geomorphological processes. Landforms are shaped by the interaction of these processes with the pre-existing landscape components characteristic of a given area. Geomorphological processes act worldwide but the results may vary depending on the landscape components; these can thus be viewed as "filters" in that they modify the effects of a process. Examples of filters include soils, vegetation, rock types, slope, aspect, time, and pre-existing landforms. The influence of a specific process on a region will vary depending on the filters present. Thus, one process may be expressed, or result, in several different landforms as illustrated in the basic landscape development model (Figure 1.5). For

example, if frost action is taking place in a valley, where each side is composed of a different rock type, the resultant valley may be asymmetric; a single process is filtered through lithology to be expressed as two different slopes. In nature, more than one process is likely to modify the landscape and more than one filter is likely to be present.

Figure 1.5: Basic Landscape Development Model

Many different filters operate on the earth's surface but they do not necessarily exert equal influence on landform development. Only one or two filters might be instrumental in the development of certain landforms or in altering the outcome of a particular process. The factors that play the crucial role in the development or destruction of a specific landform are here termed *form-controlling filters*. It is often difficult to be sure if there is only one form-

controlling filter and, if so, what that filter is. Morphological studies or process studies in a particular area over a long period of time will help determine what filters exist and to what degree they control landform development.

Thus, in a geomorphological analysis of an area, the landforms are viewed as the result of the application of one or more **processes**, expressed through one or more **filters**, resulting in various **forms**. However, to analyze an existing landform, one must also consider the *previous* sets of processes, filters, and landform expressions. Processes and filters act continuously throughout time and the landscape is a result of the continuum of activity. To determine the processes and filters active at present, it is necessary to identify the impact of inherited features; for example, the landscape inherited from Quaternary glacial processes.

The fundamental hypothesis that present landforms are an expression of past *and* present processes and filters is used as the basis for derivation of a more complex landscape development model (Figure 1.6). The detailed model highlights the most important processes, the form-controlling filters, and the effects of time, for the area. This study uses this landscape development model to examine the landforms, processes, and filters present in the Campbell Uplift, Northwest Territories. It views geomorphological form as an expression of geomorphological process. On this basis it describes the landforms of the Campbell Uplift in order to understand the processes shaping the area and offers an explanation of these processes based on the landscape development model.

Figure 1.6: Complex Landscape Development Model
Time progresses outward with the present at the centre of the diagram.

1.4 AIMS, HYPOTHESIS, AND BRIEF METHODOLOGY

The aims of the study are:

- to describe the geomorphology (the **landforms**) in the Paleozoic bedrock of the Campbell Uplift;
- to determine what **processes** and **filters** currently operate, and have operated in the past, to produce the terrain in the Campbell Uplift; and
- to present the results in a complex version of the landscape development model.

The general hypothesis presented in this report is that **the present landforms of the Paleozoic bedrock of the Campbell Uplift developed as a result of both karst and periglacial processes acting upon an inherited landscape mainly of glacial origin, and that these processes are expressed principally through the filter of lithological variation.**

This hypothesis was tested by documenting and describing the karst, periglacial, and glacial landforms and analyzing their relation to the lithology in six field areas within the Campbell Uplift. Dimensions, characteristics, and locations of the landforms were recorded in the field; these data were supplemented by rock samples and photographs. Thin sections were made of the rock samples and solubility tests performed to describe the lithology of the field areas. Different lithological features were correlated to the landforms to determine if, and how, landforms vary with particular lithological characteristics. The data were analyzed according to the landform development model and the *process*, *filter*, and *form* components were determined for the Campbell Uplift. The methodology is detailed in Chapter 3, Methodology.

1.5 SCIENTIFIC BACKGROUND

Karst geomorphology is the study of landforms produced primarily by the process of dissolution. Limestone and dolomite are the two major types of karst rock although most soluble rock can produce karst landforms (some of which are described in Chapters 2, Background, and 4, Results). Karst terrain is found throughout the world and about 1.2×10^6 km² of karst rock outcrop exists in Canada (Ford, 1987). Features characteristic of a karst landscape include calcite precipitation, solution pavements, and sinkholes.

Periglacial geomorphology is the study of landforms produced primarily by the process of frost action. A periglacial environment can exist in close proximity to an ice sheet or glacier or where one existed during the Pleistocene; they are common in areas of high altitude and latitude. In Canada about 50% of the land surface is classified as periglacial, and much of this is associated with permafrost (French, 1993, p.143). Permafrost is perennially frozen ground where temperature remains below 0°C for at least two consecutive years (Harris *et al.*, 1988, p.62). Periglacial features are described briefly in Chapters 2 and 4. A periglacial landscape includes the effects of frost shattering and wedging and of solifluction.

The Campbell Uplift is underlain by carbonate bedrock. A karst landscape would automatically be associated with this carbonate terrain if it were located in a southern, warmer, part of the world. But, in cold climates, with slow chemical reaction rates, minimal biogenic production of CO₂, and frozen groundwaters, karst is expected to be poorly developed. Karst in cold environments exists but is often more subtle than karst in warm, humid regions. As the Campbell Uplift is located north of the Arctic Circle one expects it to be modified by periglacial processes and, without the evidence of field studies, one might

assume these processes, rather than karst, to be dominant. The arid climate of the Campbell Uplift is another reason one might not assume a karst landscape would readily develop in this area. Although a lack of precipitation is not prohibitive to karst development, it usually will curtail the development of a karst landscape. The expectation that a certain climate will invariably produce an associated suite of landforms has been called the 'climatomorphological' view of geomorphology. While the theory has been discounted for many environments, it is often still invoked for karst studies and may be relevant for this study. This is further discussed in Chapter 2.3.

The most recent glacial period was the Wisconsinan glacial period from approximately 42-10 ka (Vincent, 1989, p.127-136). The glacial maximum occurred at about 21 ka (Williams *et al.*, 1993). Glacier movement and the glacial climate greatly modified existing landscapes by forming new erosional and depositional surfaces. The Campbell Uplift was glaciated during the Wisconsinan glaciation although it was only located at the margin of the glacier's coverage. Whalebacks, glacial plucking, and glacial grooves, are evidence that the study area's landscape was glaciated.

Various processes, events, and characteristics have combined to create the landscape of the Campbell Uplift. In addition to the common geomorphological processes that occur worldwide, such as mass movement, fluvial and wind action, glaciation is apparent in the inherited landscape, periglaciation can be expected in the arctic conditions, and karst can be expected on the carbonate rocks. An analysis of the morphology of the Campbell Uplift was undertaken to indicate the relative importance of the inherited glacial landscape and to see whether both karst and periglacial processes contribute to the past and present development

of the geomorphology of the Paleozoic bedrock. An analysis of lithology was undertaken to see if this is the principal filter controlling how karst and periglacial processes are expressed.

Surface morphology is a result of, and thus must carry evidence of, the processes that produce each landform. Morphology was therefore used in lieu of direct process studies to determine the processes occurring in the Campbell Uplift. Both Lauriol *et al.* (1997) and Brook and Ford (1978) used this method for their field studies of other karst topographies in northern Canada. Many other workers in the field of geomorphology have also used this principal to determine active processes in an area: for example, Dredge (1992) determined the different types and stages of weathering in the Eastern Canadian Arctic from observations of a continuum of landforms. Although one may not unequivocally deduce process from form (as process is not directly observed but inferred), this method provides a basis for landscape analysis and is a useful guide for future studies.

There are many possible filters acting in an area and the number of filters crucial to the development of the individual features of the landscape depends on the size of the area. As the number of possible filters acting in an area is too large to consider each filter in detail, it is more effective to decide which filters are likely to be important in shaping the landscape and then to test these: ie, set up the most likely hypothesis and test it; if required, later on an alternative hypothesis can be put forward. To decide which filters are important to test it is helpful to use studies of similar environments and choose the filters previously thought to be important in landscape development. The Campbell Uplift is homogeneous enough that many filters, including vegetation, climate, and time, are likely not to be the form-controlling filters. Based on research of similar areas and the reconnaissance of the area, lithology was the

principal filter selected to be looked at in this study.

Lithology encompasses the macro- and microscopic properties of a rock. These properties include porosity, texture, mineral composition, and colour. Dolomite and limestone are carbonate rocks. Dolomite, $\text{CaMg}(\text{CO}_3)_2$, is produced when magnesium replaces some of the calcite in limestone, CaCO_3 . The particular components of lithology may have varying geomorphological significance: a difference between two rock samples of one lithological property can either have no effect on the resultant landform or can cause the development of two different landforms. Thus one aspect of lithology might be the form-controlling filter.

A study by Lundberg and Ford (1994) of the karst near Dodo Creek, which exhibits many geomorphological similarities to the Campbell Uplift, emphasized the importance of lithology as a filter. The karst near Dodo Creek is 24 km southwest of Norman Wells, NWT (Lundberg and Ford, 1994). It is located in a permafrost zone of Canada and has a dry climate, as does the Campbell Uplift. Completely dolomitized limestone, from the late Ordovician-early Silurian period (around 438 million years ago) is the host rock in the Dodo area. This rock exhibits little frost damage in some areas, for example the Dodo pavements, but in others the rock is completely reduced to rubble. Lundberg and Ford argued that these different landforms are primarily due to variations in the lithology of the carbonate rock. The surfaces that were most affected by frost action were the less pure and less massive dolomites. Lithology was also shown to be an important filter in the formation of other arctic carbonate landforms. In a study of the area around Igloodik and Hall Beach, Northwest Territories, Dredge emphasized the importance of rock structure in determining the "size, type, and

location of weathered carbonate bedrock" (Dredge, 1992, p.314).

The similarity between the Dodo karst area and the Campbell Uplift suggests that lithology has played an important role in the dolomite and limestone structures of the Campbell Uplift. Since lithology varies throughout the Campbell Uplift while climate, vegetation, and other filters act, essentially, homogeneously throughout the region, lithology was thought likely to be the most important filter in the Campbell Uplift.

1.6 USEFULNESS OF STUDY AND RATIONALE FOR WORK

There is a limited amount of information on karst in cold, northern environments, including material about Canada. This quantitative study of morphology will add to the existing knowledge. The data set presented may be used as a reference for future research.

A lack of literature about cold and/or northern regions in English language karst literature is noted. The paucity of studies is attributed to the difficulties and expense of field research required to report information about karst in these regions. Therefore, this study will contribute significantly to our knowledge of cold region karst in Canada.

The inclusion of measurements of each type of observed landform is an important contribution to cold region karst studies. There are few, if any, published studies that include actual measurements and none claim to have an adequate sampling base to represent a population of features. This study is one of the first to present data about cold regions karst landforms and documents 2622 metres of surveyed traverses.

Before this study no one had extensively documented the geomorphology, particularly the karst landforms, of the Campbell Uplift. J.C. Ritchie (1976) stated that "the area is

unrivalled as a natural laboratory that is accessible for teaching and research in several branches of the natural sciences" (p.70) and that it is "uniquely and richly endowed with natural phenomena" (p.75). Although Ritchie was successful at describing the biology and conveying a sense of its value, he did not address the geomorphology of the Uplift.

This study of the geomorphology of the Campbell Uplift was undertaken in response to the comments by Ritchie. It is an attempt to add geomorphology to the popularly valued ecosystem components usually considered worthy of preservation and addressed in environmental assessment studies. Landscape has great intrinsic value and is one of the necessary components of any ecosystem. The Campbell Uplift adjoins the Gwich'in Territorial Park and is currently being assessed as another potential resource for people using this park. Documentation of the geomorphology and description of the processes that have contributed to the formation of the landscape will potentially aid in the development of trails through the park and trails in the Campbell Uplift.

1.7 CONSTRAINTS AND LIMITATIONS OF THE STUDY

A more in-depth analysis of the processes and filters acting in the Campbell Uplift would require long-term investigation. However, one field season was deemed sufficient for data collection for this study as it is the first attempt at documenting the geomorphology of the Paleozoic bedrock area of the Campbell Uplift. Potential limitations such as access and time of year are discussed in Chapter 3, Methodology. The small budget for this project limited the amount of time spent in the field, the number of field assistants, and the type of equipment and transportation. Helicopter transportation to and from sites that were

inaccessible by foot, boat, or vehicle was not possible for this reason. For future research in the Campbell Uplift increased funding for the project would permit increased time in the field and also enable researchers to cover a greater surface area than this study as more sites would be accessible by using more efficient transportation.

The project described is part of the requirements for a masters degree and, as such, it was necessary to impose a limit to the scope of the project. Due to the constraints imposed on the study, the fieldwork did not include chemical and hydrological studies but these would be an excellent focus for future research.

1.8 THESIS ORGANIZATION

This first chapter has laid out the academic basis for this study of the Campbell Uplift. The next chapter provides background information on lithology, karst and periglacial geomorphology, glaciation, and the effects of their interaction(s). A discussion on the effects of a northern climate on karst processes and how lithology and morphology are related is also included. It concludes with a description of the study area including brief sections on geology, glacial history, climate, and vegetation. The third chapter details the methods used to study the geomorphology of the Campbell Uplift and their rationale. The results of the field and laboratory work are presented in Chapter 4, Results, along with landform and lithological classifications for the study area and their associated descriptions and field examples. The relations between lithology and landforms are explained in Chapter 5, Analysis, and an explanation is presented. This study is concluded and summarized in Chapter 6, Summary and Conclusions.

CHAPTER 2: BACKGROUND

2.1 PREAMBLE

The four basic topics relevant to this study are lithology, karst, periglaciation and glaciation. They are presented in this chapter which reviews some of the important definitions and issues relating to the lithology and geomorphology of the Campbell Uplift.

Lithology and its relation to landscape is discussed in section 2.2 and is hypothesised to be a form-controlling filter in the study area. Next, section 2.3 defines karst geomorphology and describes karst landforms because they are important in shaping the landscape of the study area. Although karst hydrology is not examined in this study of the Campbell Uplift, a basic overview is presented for a complete understanding of karst environments. Karst dissolution and the effects of carbon dioxide and temperature on this process are next discussed. The theories of karst development, particularly the climamorphological and evolutionary theories, set the stage for the explanation of the issues surrounding karst in cold environments. Periglacial processes are hypothesised to be active in the Campbell Uplift and are described in section 2.4 followed by a description of periglacial landforms. Similarly, glaciation in Canada is examined and glacial landforms described in section 2.5. The interaction of karst and periglacial processes and the effects of glaciation on these processes are considered in sections 2.6 and 2.7. The final section of this chapter describes the Campbell Uplift, including its geology, glacial history, climate and vegetation, and a brief introduction to its geomorphology.

2.2 LITHOLOGY

Lithology is often an important variable in a landscape and is defined in the Oxford Dictionary of Earth Sciences as "the description of the macroscopic features of a rock, e.g. its texture or petrology" (1990, p.219). Lithology herein will also include the microscopic properties of a rock, such as insoluble and iron content, crystal size and shape. Other lithological properties include strength, porosity, permeability and mineral composition (Sparks, 1971, p.9-60). Macro- and microscopic rock properties can be determined using various field and laboratory methods including hand specimen description, percent solubility tests, and thin section analysis.

2.2.1 Karst Rock Characteristics

Lithological characteristics of the host rock as well as the effects of tectonism are important controls on morphology and on the effects of karst processes (Ford and Williams, 1989, p.374-375). Development of karst landforms is attributed to high rock solubility and a well developed, usually secondary, porosity. The characteristics and percentage of voids within a rock determine its porosity. Size, distribution, and nature of the pores are important in karst because they affect the hydrological and erosional processes in and on the rock.

Primary porosity is defined as inherited porosity, while secondary porosity is acquired as discussed below (Ford and Williams, 1989, p.159). Most carbonates have a low primary porosity (Jennings, 1985, p.35; Ford and Williams, 1989, p.133; Tucker and Wright, 1990, p.25-27) which is enlarged through groundwater circulation. Post-lithification tectonic action creates various scales of fractures; the dissolutional enlargement of the fractures will create

high secondary porosity. A high secondary porosity can also develop during diagenesis, for example dolomitization. The secondary porosity of carbonate rocks can be as much as 3.5% (Ford and Williams, 1989, p.133) and is important in the development of karstic features. In karst rocks, particularly hard Paleozoic limestones, the secondary porosity continually increases through geomorphological processes while the primary porosity tends to be fixed prior to the onset of karst processes.

Porosity and permeability are interrelated. Permeability is the ability of a rock to transmit fluid, notably water in karst rocks, and is determined by pore size and shape, pore connectedness, and other physical properties of rock (Ford and Williams, 1989, p.130). The greater the permeability, the greater the possibility for karst waters to enter and dissolve the rock and thus create karst landforms. Karst rocks typically have low primary permeability but high secondary permeability. Joints and fractures are passageways for water to enter the rock. Orientation and frequency of joints are important. Interconnectedness of joints increases the permeability of the rock and a greater surface area is available for the karst process of dissolution.

2.2.2 Lithology and Geomorphology

Both laboratory tests and field observations support the idea that lithological and structural controls are important in landscape processes (Bloom, 1998, p.139; Dredge, 1992; Jennings, 1985, p.177-190). Fundamental lithologic properties such as grain size, porosity, and permeability have been found to be significant. For example, Glasser *et al.* (1998) determined from a study in Svalbard that lithological and structural characteristics of the

parent rock play a crucial role in determining the style of glacial erosion, particularly of the bedrock surface wear beneath glaciers. Specifically, the dominant surface wear is caused by glacial abrasion in poorly jointed, homogeneous or massive lithologies such as marbles (Glasser *et al.*, 1998). Allison and Goudie (1990) studied the effect of rock mass strength on the form of rock slopes in tropical limestone in the Napier Range of Australia. They concluded, among other things, that the form of the slopes is related to the difference in the limestone lithological units and rock mass parameters.

From field studies in the Canadian Arctic, Dredge (1992) determined that the macro- and microstructures in bedrock are conducive to breakdown. "Although temperature and moisture conditions determine which types of weathering are probable, the role of bedrock structure and lithology is crucial to understanding the creation and distribution of broken rock forms" (Dredge, 1992, p.320). She concluded that water infiltrates the joints, vugs, and weak beds in the rock and creates sites where the volumetric expansion of water as it freezes to ice, or the effects of hydraulic freezeback processes, will fracture the rock. Ice expansion and hydraulic processes tend to occur in large voids which are part of the macrostructure of the rock such as joint openings, bedding discontinuities, and solution zones (Dredge, 1992). Water enters the rock through joints and travels laterally along bedding planes and partings. It will enlarge these passageways so that processes acting in voids and large pores, such as ice expansion and hydraulic processes, can become active (Dredge, 1992). Lithological and structural properties of soluble rocks play a major role in determining the resultant landform. Both the macro- and microstructures of the rock will play a role in the physical and chemical reactions causing the breakdown of the rock. The mineral composition of the rock beds will

determine the final size of the product of both the mechanical and chemical weathering of the rock (Dredge, 1992).

Lithological filters act in conjunction with other filters and geomorphic processes and the resultant landforms depend on the specific combination of these factors. Lithology is not the only constraint on landform development but together with climate, it has a major role in morphological development. Alone, neither climate nor lithology determine morphology but combined with glacial legacy, present and past geomorphological processes, and other filters, such as vegetation and human influence, a more comprehensive understanding of landform development can be assembled.

2.3 KARST GEOMORPHOLOGY

Karst geomorphology is the study of landforms created as a result of dissolution (Ford and Williams, 1989, p.1). Karst terrain throughout the world is defined by its particular hydrology and specific landforms related to high rock solubility. This kind of terrain is found "where soluble rocks have been greatly modified, above and below the surface, by the dissolving action of water" (Trenhaile, 1990, p.196). Sweeting describes true karst landscapes as existing where all water circulates underground, where no water is found on the surface. She defines karst terrain as "a solution-controlled landform type, characterised by an exclusive surface morphology, subsurface drainage and collapse features, which is specifically developed in calcareous rock" (Sweeting, 1973, p.333). Roglič (1972) is more specific about how water travels in karst, including in his definition that water circulates in fractures, fissures, joints and other cavities (Roglič, 1972). Jennings (1985) defines karst as

"a terrain with distinctive landforms and drainage arising from greater rock solubility in natural waters than elsewhere" (Jennings, 1985, p.1) which emphasises the comparison of karst terrain to other places; and that rock solubility is not absolute but comparatively higher. The common characteristics of the preceding definitions are the effects of water and the relationships of surface landforms to underground drainage. Geomorphic processes do not usually work in isolation and karstic dissolution is no exception. Chemical dissolution of carbonate rock is not necessarily the only process that occurs in karst terrain although it is generally the most important (Jennings, 1985, p.1).

The dominant process in karst systems is the aqueous dissolution of minerals (Ford and Williams, 1989, p.1). Dissolution greatly impacts the form of karst rocks by chemically altering their appearance over time. The major karst rocks, composed largely or entirely of soluble minerals, are limestone (CaCO_3) and dolomite ($\text{CaMg}(\text{CO}_3)_2$). Evaporites (anhydrite, gypsum, salt) are more soluble than limestone or dolomite and are less likely to be found as outcrops. Nevertheless, the interstratal solution of evaporites is important in the development of karst features (Ford and Williams, 1989, p.27). Karst landforms and features develop in evaporite rocks such as gypsum, anhydrite, and salt, although the best examples of karst are found in carbonate terrain.

2.3.1 Karst Landforms

Karst landscapes have distinctive landforms that either funnel water to the underground plumbing system or are created from this system where the water is discharged. The surface morphology of karst terrain is directly related to the underground karst processes.

Dissolution on and below the surface determines many of the surface features. Surface features range in size from very small (< 1 cm) to very large (> 1 km). The scale of karst landforms is related to the properties of the karst rock, available water and carbon dioxide, temperature, relief, and the length of time over which karst processes have acted. More detailed descriptions and illustrations of the karst features found in the Campbell Uplift are located in Chapter 4, Results.

Small-scale features, termed karren, include solution pits and grooves which may vary from one centimetre to a few metres in length or depth. Limestone pavements (clint-and-grike assemblages) are dissolutionally modified scoured surfaces often with dense karren in one area. Clints are joint-bounded surfaces of limestone (or dolomite) which comprise the horizontal surface of a pavement. The whole pavement may extend many kilometres or it may be only a few metres in width and length. Pavements, which are often nearly level as a result of the lateral scour, may be dissected by grikes which are solution-widened joints cut into the surface (Ford and Williams, 1989, p.389).

At the middle scale, dolines are closed depressions that vary in size from a couple of metres to as large as a thousand metres in diameter. The most common types of doline are formed through dissolution from above (dissolutional dolines) or below (collapse dolines).

Large-scale karst features include the larger dolines and towers. Poljes are very large closed depressions with flat floors. The size of the flat bottom of a polje varies from as little as a few tens of metres square to as large as several tens of kilometres square (Ford and Williams, 1989, p.428-9). Labyrinth karst is another large karst feature which is made up of large assemblages of squared, or 'box', valleys. It is more descriptively called corridor karst

as it resembles long corridors that often intersect at right angles. Examples of this type of karst are known in tropical and temperate rainforests as well as desert and semi-desert areas (Ford and Williams, 1989, p.391; Brook and Ford, 1978).

2.3.2 Karst Hydrology

Karst rocks are modified by both the hydrological and geochemical subsystems of the environment. The hydrological characteristics of karst terrain are substantially different from non-karst terrain. There are three distinctive features of karst hydrology:

1. Both diffuse and concentrated circulation characterize the karst hydrologic regime. Slow diffuse flow can enlarge joints over a large area by infiltration of rainwater. On the other hand, water can quickly flow through conduits or reach subsurface levels due to concentrated points of infiltration which lead to high groundwater circulation (Sweeting, 1973, p.250).

2. A continuous water table may be absent. A discontinuous water table often characterises karst and is controlled by lithology and structure. The water table may be at a different level within the same karst region (Sweeting, 1973, p. 235; Jennings, 1985, p51-58; Ford and Williams, 1989, p.8). Related to the idea of a discontinuous water table is Cvijić's idea of the relationship between hydrology and surface morphology. He proposed that there are three hydrographic zones in fully developed karst: a dry zone, a periodically inundated zone, and a zone that is permanently inundated (Sanders, 1921). The hydrographic zones are dynamic as the upper zones eventually replace the lower zones and the once inundated zone will become dry. Cvijić's work laid the foundations for many of the current ideas in karst

study. His ideas are pivotal to karst studies because the continuous modification of the hydrologic system is presently seen as an important and unique feature of karst (Ford and Williams, 1989, p.252).

3. Groundwater does geomorphological work by chemical dissolution of the rock. In all terrains, water will physically and chemically weather and erode surfaces but in karst terrain (assuming sufficient time) it will chemically dissolve a much greater quantity of rock than in terrain composed of less soluble rock. Dissolution is a defining feature of karst.

2.3.3 Karst Dissolution

The dissolution of limestone occurs when carbon dioxide and water react to produce carbonic acid. The acid reacts with calcite (CaCO_3), the major component of natural limestone and dolomite, to produce bicarbonate. The following equations describe the chemical reactions involved in limestone dissolution, the fourth is a summary of the first three components:

(after Ford and Williams, 1989, p.56)

Dolomite, $\text{CaMg}(\text{CO}_3)_2$, follows a slightly different set of reactions summarised as:

(Ford and Williams, 1989, p.57)

The evaporites, anhydrite, gypsum, and salt, dissociate directly in water (Ford and Williams, 1989, p.51-53).

In carbonate dissolution the active components are the rock, carbon dioxide, and water. Carbon dioxide must be incorporated into water so that it can dissociate and react as in equations (1) through (5). The amount of carbon dioxide dissolved in the water determines the equilibrium solubility and is controlled by the availability of the gas and by temperature (Ford and Williams, 1989, p.63).

2.3.4 Carbon Dioxide and Temperature

There are many controls on carbon dioxide availability and effectiveness; temperature is of special importance. Soil CO₂ is a very important source of carbon dioxide for dissolution of carbonates and varies with "soil type, texture and horizon, depth, drainage and exposure, types of vegetation cover, soil flora and fauna, with seasonal and shorter period warming and wetting" (Ford and Williams, 1989, p.64). Soil structure can greatly affect the amount of CO₂ production and retention. For example, very permeable soil will have less available CO₂ than fine-grained soils.

The effect of temperature on rates of karst dissolution is relatively well understood although it may be more complicated in local situations. The solubility of carbon dioxide is inversely proportional to temperature. In 1959, Corbel argued that since cold temperatures increased the solubility of carbon dioxide, the capacity for carbonate dissolution in cold regions was greater than in more temperate climates. Unfortunately he disregarded other effects of cold environments, such as biogenic soil CO₂, so that his conclusion is faulty. The

amount of carbon dioxide in the soil (discharged, for example, by plant roots, bacteria, and other soil organisms) is more important in terms of dissolution than the solubility relation with temperature (Ford and Williams, 1989, p.64; Sweeting, 1973, p.25). Therefore, on average, limestone dissolution rates are lowest in cold and alpine environments as soil carbon dioxide production is low in these regions (Ford, 1993). Nevertheless, karst processes occur and morphological features are found in cold environments. Examples of karst in the north include the Nahanni karst, NWT, Canada (Brook and Ford, 1978), the Akpatok Island karst, NWT, (Lauriol and Gray, 1990), and the karst in Glomdal, Svartisen, Norway (Lauritzen, 1984). The effect of climate on karst terrain has been debated extensively. The debate is summarized in the following section.

2.3.5 Karst Development Schemes

Until the 1960s and 70s, scientists considered climate to be the controlling component in most landform development, i.e. given a specific climate a particular landform would develop (Bloom, 1998, p.3). This widespread claim was particularly relevant for karst studies as exploration in tropical areas brought reports of forms extraordinary to the eyes of academics used to the karst features of Europe. The classic karst of temperate regions, exemplified in the Krs (“karst”) region of Croatia, has a landscape dominated by dolines; exploration of tropical regions revealed a much more dramatic landscape often dominated by extremely steep residual hills, either towers or cones, and separated by flat plains in the case of towers or deep cockpit depressions in the case of cones. For example, H. Lehmann (1936) studied the karst in Java and concluded that the limestone cone landforms developed in this

location were controlled directly by the humid tropical climate. If typical features of a humid tropical climate were found outside this climatic zone then their development was attributed to past climatic conditions that are no longer prevalent.

An alternative, less widely accepted, framework was that karst landforms followed instead an evolutionary sequence in which the landscape reflected a particular stage in the sequence (Grund, 1914). In this scheme young karst is characterised by dolines in large flat areas whereas mature karst has large dolines and uvalas between cone shaped hills appropriately described as "eggbox topography". Old karst has only residual hills and the baselevel is much lower than in the young stage. Grund gave the example of young karst found in the Dinaric Mountains of Europe. He cites the landforms of Java and Jamaica described by Daneš as examples of mature karst (Grund, 1914). However, in H. Lehmann's morphological study of the karst in Java (1936) there is some debate as to the role of climate and the evolutionary schemes of development. The karst described in Java is a cockpit karst which looks like a "pock-marked" landscape with rounded hills that reach a hundred to two hundred feet high. Lehmann identified the warm, humid climate as the controlling factor on this specific karst landscape and questioned the claim that it is a mature karst as defined under Grund's framework of karstic evolution.

The claim of climate dictating karst landscapes has been reassessed over the past 30 years (Jennings, 1985, p.192). The overriding importance of climate in geomorphological explanation has given way to a more balanced awareness of the complexities of controls and filters. White (1984) argues that temperature is less important in controlling karst development than other factors such as precipitation and its duration, lithology, and pre-

existing landforms. In a study of the Nullarbor karst in Australia, Lowry and Jennings (1974) attributed this karst to climate but tectonic setting, although less important than climate, was also deemed a fundamental control on the Nullarbor karst. Jennings (1985, p.179) cites the example of Panoš and Stelcl (1968) who attributed the control of karst development of Cuban mogotes to geological structure and not to humid tropical conditions as earlier thought by Lehmann *et al.* (1956). In 1978, Brook and Ford published a paper on the origin of labyrinth and tower karst and therein suggested that "the relationships between karst morphology and climate be reassessed" (Brook and Ford, 1978). They based this conclusion on the fact that the cold climatic region of the Nahanni (NWT, Canada) produced tower karst similar to that which has developed in the humid tropics. Structural control in the Nahanni karst exemplifies how landforms, originally described as climate specific, may actually be the result of controls, or filters, other than climate. In another example of controls on karst landscape development other than climate, Pope *et al.* (1995) challenged the assumption that chemical weathering, because it is usually most dramatic in wet regions, must have a minor role in dry regions. They argued that the scale of the process affected the amount of chemical activity that was evident. This contributes to the argument that chemical solution is possible in areas that were previously eliminated for climatic reasons.

Sweeting (1973) sums up the situation of karst development schemes well: "As in many scientific developments, the role of climate in the formation of karst landforms has been overstated and many non-climatic factors neglected" (Sweeting, 1973, p.131). The debate about climatic control of karst development has led to further karst studies. The result is the understanding that landscape does not necessarily behave according to a single model and that

many factors contribute to karst development. The fundamental requirements, available carbon dioxide, moving water, and soluble rock, are incorporated into a complex control scheme including climate (temperature and precipitation), vegetation, geological history, and lithology. The degree of the influence of these factors is not consistent throughout the world and every karst area will have its own controlling factors and filters. The notion of cold climates prohibiting the development of karst is no longer seen as valid although the effects of cold temperatures, minimal precipitation, and specific climatic regime need to be considered when describing cold environment karst.

2.3.6 Karst Environments in the Northern Hemisphere

A lot of karst is located in warm, humid regions of the world rather than in polar regions. If water is frozen it is not available for dissolution. Therefore, it can be hypothesised that karst located in cold environments developed when the region experienced warmer conditions. The karst is then referred to as relict. On the other hand, Ford (1984, 1987) and van Everdingen (1981) have suggested that the effects of limestone solution are prominent in cold (as well as warm) environments despite the fact that permafrost and periglacial activities, as well as frozen water, characterize these environments. Sloan and van Everdingen (1988) also emphasize the idea that karst development is not limited to warm, humid regions when they conclude that development of karst is not necessarily impeded by the presence of permafrost (specifically frozen water) and is not, therefore, a relict from a warmer environment. The karst of the Akpatok Island in the Northwest Territories, which lies within the continuous permafrost zone, shows the importance of subterranean drainage

which is augmented in the spring (Lauriol and Gray, 1990). This karst is active despite existing within the zone of continuous permafrost.

For karst to exist anywhere there are three components necessary for its development and maintenance. One necessary component is soluble rock. Limestone, dolomite, and evaporites are found in the arctic, meeting this requirement. The second component necessary for karst development is carbon dioxide. In general, northern regions are characterised by low production of carbon dioxide. However, there is a substantial increase in CO₂ production in spring and summer when the vegetation is growing and blooming. Spring bloom in the Arctic greatly increases available respiratory CO₂ compared with winter and fall values (Woo and Marsh, 1977). An increased number of daylight hours in the summer permits biogenic activity and vegetation to continue natural processes, including an increased respiration rate, for a greater amount of time in the north than elsewhere. Although this does not entirely compensate for long winters, it does contribute to the notion that karst dissolution in the north is possible.

The third component required for karst development is water. In northern regions ice and snow dominate the landscape for a large portion of the year but water becomes available during the short spring and does not freeze again until fall. Water comes from ice melt on rivers and lakes, snowmelt, and melting of the active layer. The average annual temperature in the subarctic ranges from -6 to 0°C and in the Arctic from -12 to -7°C but temperatures can reach a high of 30°C in the summer in the subarctic and will average 5-15°C for as long as 3 months (Rouse, 1993). Therefore, water can circulate over and under karst terrain for a significant part of the year and contribute to karstic dissolution. Open fractures and fissures

which develop in many types of terrain, but specifically in permafrost carbonate environments, facilitate groundwater movement. This increases the possibility of movement of perennial groundwater discharge in cold environments (Clark and Lauriol, 1997). Another important consideration is the speed of spring thaw in the subarctic and arctic which precedes spring bloom. This event causes a sudden large increase in available water and accentuates the effects of increased amounts of soil CO₂ as more water is also available for karstic dissolution. Thus, in cold environments, karst development tends to be more active in the summer due to a general increase in running water as well as more respiratory CO₂ from biogenic activity (respiration from bacteria, fungi, cyanobacteria, worms, etc.) and an increased amount of plants.

Seasonal variations cause more karst activity in the warmer months and a decrease or absence of karst forming processes in the winter due mainly to a lack of moving water. This feature is not unique to northern regions, as seasonality is experienced in many other parts of the world. It is significant because other processes, such as frost wedging, might dominate the landscape for a longer period than karst processes and often during different seasons. Karst processes, for example, will be more important than periglacial processes in the summer and vice versa in the winter. On the other hand, seasonal freezing can contribute to unique karst features. The gypsum speleothems, called yozh, that are found only in the Pinega Region of Russia develop in areas that have been subjected to winter seasonal freezing (near entrance areas, wall fissures, and ceilings) (Korshunov and Shavrina, 1998). Without the extreme seasonality that characterises northern regions these speleothems might not form.

Another reason for the possible existence of karst in northern regions is the potential

for karst systems to develop where the hydraulic gradient is steep (Ford, 1993), regardless of the environment. The greater the slope on which water flows the greater the chance water will concentrate, flow downhill, and dissolve the rock along its path. Thus, wherever there is a high hydraulic gradient, for example, on Akpatok Island (Lauriol and Gray, 1990), karst potentially can develop despite the inhibiting effect of permafrost.

2.4 PERIGLACIAL PROCESSES

Periglacial processes are characterised by permafrost-related processes, such as thermal contraction and thawing of permafrost, frost action (specifically frost heaving), ice segregation, and intrusive ice (French, 1996, p.5). Permafrost is perennially frozen ground where temperature remains below 0°C for at least two consecutive years (Harris *et al.*, 1988, p.62). Areas within permafrost are not necessarily frozen because some materials remain unfrozen due to depressed freezing points caused, for example, by dissolved mineral enrichment of the groundwater. Permafrost regions are generally associated with periglacial regions but "there is no perfect spatial correlation between areas of intense frost action and areas underlain by permafrost" (French, 1996, p.4). Periglacial conditions exist, for example, in the southern part of the Rocky Mountains of Canada that are underlain by permafrost. Permafrost and ice segregation are considered diagnostic features of periglacial environments. Many processes occurring in periglacial regions are not necessarily restricted to these regions but are particularly significant there due to their frequency, duration, or intensity (French, 1996, p.5).

Permafrost conditions vary spatially in Canada and are divided into four categories

(Figure 2.1). The southern limit of continuous permafrost is approximated by a mean annual temperature of -8°C whereas the southern limit of discontinuous permafrost is associated with the -1°C isotherm (Bloom, 1998, p.310). However, these are merely approximations since they are based on the air temperatures which are commonly several degrees different from the mean annual ground temperatures.

Permafrost will aggrade, degrade, or remain unaltered depending on surface and climatic conditions. The upper part of the ground is the active layer and thaws seasonally. The active layer and, in time, permafrost in general, changes depth depending on snow cover and duration, vegetation changes, fire, and general climatic conditions, but does not usually change dramatically from year to year. Local changes in these factors will alter the thermal regime of the area but will not necessarily affect the larger, more general, permafrost zone. On the other hand, an increase in global temperatures, for example, may affect the overall distribution of permafrost on a continent-wide scale. On the local level, permafrost can be considered to have similar characteristics providing the terrain, vegetation, and climatic conditions are similar throughout the area.

Figure 2.1: Permafrost distribution in Canada (after French and Slaymaker, 1993, p.22)

Periglacial activity is the freezing and thawing of rock, soil and water. The physical weathering processes of frost action, including frost shattering, wedging, and heaving, are widely accepted as dominant processes in northern periglacial environments (French, 1996, p.5). Some lithologies are more susceptible to frost action than others (French, 1996, p.5). For example, frost heave is predominant in fine-grained unconsolidated material due to the unfrozen water content in this type of soil and its low permeability. High pore water pressures promote frost heave and the formation of massive ice (Williams and Smith, 1989, p.30-1). Coarse-grained sediments around fine-grained are often observed in massive ice formations. It is thought that the coarse-grained material supplies the fine-grained, frost susceptible material, with water which aids the frost heave process.

Various types of ground ice characterize permafrost environments. Segregation ice is the result of water migrating due to the freezing-induced lower pressure of water at the ice-water interface (Williams and Smith, 1989, p.32; French, 1996, p.5). Intrusive ice is the result of an elevated hydrostatic pressure in the water adjacent to the soil and is therefore the opposite of ice segregation and frost heave. Ground ice production and frost action are the principal geomorphic processes in most periglacial regions and create many of the landforms.

Where there is not a lot of soil in permafrost areas, ice near the surface may be lacking altogether. However, ice segregation and intrusive ice can be present. Water is present in fractures and joints as well as in the pores of bedrock. This water will freeze and can cause "bedrock heave", the uplifting of bedrock blocks (Williams and Smith, 1989, p.157). In areas where bedrock is visible at the surface, bedrock heave is the predominant process shaping the landscape. French (1996, p.49) suggested that the widespread but minor solutional forms

evident on bedrock surfaces indicate that dissolution can effectively accelerate rock disintegration by frost weathering. As in most geomorphic situations, the landforms in periglacial regions may not result from a single process (frost action) as more than one weathering process may be involved.

2.4.1 Periglacial Landforms

Periglacial processes may create a distinct landscape characterised by large amounts of scree, patterned ground, and freshly altered surfaces due to frost action, especially in the poorly vegetated regions of the arctic tundra. Although the subarctic is relatively well vegetated, rock rubble and solifluction surfaces are common. Solifluction surfaces resemble wave-like flow forms on the surface of terrain usually covered by a shallow layer of soil (Williams and Smith, 1989, p.22) and are described in greater detail in Chapter 4, Results.

Characteristic landforms of the periglacial environment range from very small (< 1 cm) to very large (> 1 km). Small scale features include frost-shattered and cracked rock. The size of the rock fragments depends on the rock properties but usually the pieces are several centimetres long. Larger rock pieces can be the result of frost shattering but might be formed by frost wedging. Frost pockets are indentations in a vertical (or near-vertical) rock surface that resemble a pocket in a wall with a horizontal surface at the bottom and can range in size from only ten centimetres to as large as a few metres.

Large scale periglacial features include examples such as pingos and patterned ground. Pingos are large, ice-cored, mounds averaging about 50 metres in height (Williams and Smith, 1989, p.150). Patterned ground develops from the effects of freezing and thawing soils

(Williams and Smith, 1989, p.168-173) and is a spectacular sight from the air when it covers a large surface area. Patterned ground is made up of many polygons which are about 2 to 3 metres at their largest width (Williams and Smith, 1989, p.22-24).

Periglacial landforms can be divided into three categories: those associated with aggradation of permafrost, those associated with degradation of permafrost, and those associated with permafrost (but not part of the first two categories). Ground ice, ice wedges and their polygons, and pingos, are landforms associated with the aggradation of permafrost. Thermokarst (landforms resembling karst features but formed due to periglacial processes), thaw lakes and depressions are landforms associated with degradation of permafrost. Other landforms generally associated with permafrost include patterned ground, solifluction surfaces, palsas, peat plateaux and frost mounds, rock glaciers, and frost heave landforms.

Periglacial landforms are associated with frost action or the effects of low temperature on water (specifically with increased solute concentrations) and the presence or absence of permafrost. The landforms in periglacial regions also reflect the effects of general geomorphic processes such as mass movement and wind action and the legacy of glacial processes (French, 1996, p.11). Chapter 4 provides details and illustrations of the periglacial landforms in the Campbell Uplift.

2.5 GLACIATION

There have been many glacial episodes in Canada although their timing and extent of ice coverage are controversial, especially close to the estimated limits of both area and time. As such, a discussion of glaciation in Canada is presented prior to a description of glacial

landforms, the result of glacial processes.

2.5.1 Quaternary Glaciation in Canada

Canada has been glaciated more than once although the exact number of times is unknown. Deep sea cores and Milankovitch's calculations (Clark and Bartlein, 1995) suggest that there is a possibility of seventeen glacial-interglacial cycles in the past two million years (Ford *et al.*, 1984) although only nine clear cycles are usually agreed upon (Bradley, 1985, p.185). However, because ice build-up is dependent on complexities of moisture supply in addition to simple solar insolation, it is difficult to determine whether all the glaciations actually occurred on the continents and, if so, to what extent. The classical conception of North American Quaternary glacial history is of four major glacials and three interglacials. The evidence for glaciations in Canada and the United States indicates that the oldest glaciation in the American Midwest occurred about 2.5 million years ago and the last glacial stade was from 30 000 y BP to between 15 000 and 5000 y BP (Ford *et al.*, 1984). The only glacial stade that is incontrovertible is the last, known as the Late Wisconsinan (or classical Wisconsin).

In Canada the number of glacial periods endured varies with location. It is hypothesised that "not less than four different Cordilleran and four different Laurentide glaciations" (Ford *et al.*, 1984, p.223) occurred at the cold, arid margins which include the Yukon Valley and the Mackenzie Mountains, whereas evidence from the active margins, including the west coast, southern Ontario and the Atlantic, suggest that "more than four glaciations in less than the last 1 million years" (Ford *et al.*, 1984, p.223) occurred in these

areas. Despite uncertainty in the number of Quaternary glacial cycles in different parts of Canada, there is evidence that glaciers have passed over the land and altered its appearance. Unfortunately, a lack of knowledge of the number of glacial periods in an area also means that it is unknown how many times other geomorphic processes and landscape development in an area have been interrupted.

2.5.2 Glacial Landforms

Glaciers alter the landscape by forming erosional and depositional landforms. Depositional processes vary depending on whether the glacier is actively flowing or stagnant and if the landforms are found beneath the glacier or at the surface margin (Chorley *et al.*, 1984, p.452). Erosional processes can be divided into abrasion, also called scouring, and plucking, or quarrying. Existing geomorphology, geological structure, proximity to the edge of the glacier, length of time glaciated, and direction of flow of the glacier combine with the processes of erosion and deposition to form the resultant glacier landforms (Bloom, 1998, p. 373; Chorley *et al.*, 1984, p.431; and Hambrey, 1994, p.81&110).

The effects of the movement of glacial ice and its contents, usually rock, are recorded in glacial features such as glacial striations, chatter marks, and concentric grooves. These features can resemble little scratches on bare rock surfaces that are only tens of centimetres long to large gouges that are metres wide and even hundreds of metres long. Drumlins, roches moutonnées, and whalebacks are hill features created by the erosive powers of a glacier and differentially formed due to the pre-existing landscape and the direction of glacier movement. These features usually range in length from several metres to a few kilometres,

with smaller height and width dimensions. Deposition by glaciers can fill in large valleys or just leave a thin veneer of glacial debris to coat the surface. Erratics are pieces of rock of any size that are removed from their place of origin, transported by the glacier, and then deposited elsewhere. Erratics vary greatly in both degree of weathering and distance transported and can dot an otherwise planar surface. More detailed descriptions and illustrations of the glacial features in the Campbell Uplift are located in Chapter 4, Results.

2.6 COMPETITION BETWEEN KARST AND PERIGLACIAL PROCESSES

In any climate, karst processes are in competition with surficial erosional processes, such as mass movement, fluvial, and eolian processes, to modify the landscape. In cold environments, where the terrain is often depleted of water, solution of karstic rocks may be limited and morphological evolution may be dominated by other geomorphic processes. Permafrost can be expected to greatly decrease karst activity. However, if other geomorphic processes are not very active then the cumulative effects of slow dissolution over time will eventually lead to a karst landscape. Thus, karst dissolution can be the dominant geomorphological process in a northern region even if other processes also occur.

Permafrost regions characteristically do not maintain a large quantity of circulating groundwater as most is frozen. The exceptions to this are the active layer, which thaws during the warmer months of the year, the subpermafrost zone, and some areas within the zone of discontinuous permafrost. Therefore, permafrost would seem to be a barrier to karst development and maintenance. The situation is actually very complex and the possibility of karst must be examined on an individual case basis. More than one factor controls karst

development, therefore, permafrost is not always a strong enough factor to completely deter its formation.

Where there is widespread permafrost in mountainous regions the situation for karst development is complex. For example, the limestone and dolomite terrain of the Nahanni karst in the Northwest Territories was found to display three distinct zones of karst development. The three zones are 1) the complete permafrost (small amount of karst), 2) periodic impedance of drainage (moderate amount of karst), and 3) unimpeded drainage (more extensive amount of karst) (Ford, 1987; Ford and Williams, 1989, p.491). The Nahanni karst is dominated by active karst processes and the typical labyrinth features are still sharp and distinct without much visually apparent degradation. This karst was used as the basis for a zonal model describing the relationship between permafrost and karst drainage in alpine permafrost (Ford, 1987; Ford and Williams, 1989, p.489-91).

The Mt. Kindle Formation dolomites are exposed in the Dodo area of the Carcajou region (NWT), a semi-arid, arctic upland above the tree line that was last glaciated about 12 ka (Lundberg and Ford, 1994). The Dodo area is in the zone of discontinuous permafrost. The dolomites of Dodo show clean-cut clints and grikes instead of the general rounded solution features of many of the world's dolomites. The pavements in the Dodo karst are an example of active karst in a glaciated permafrost environment. However, in Tsi-it-toh-Choh, an unglaciated area of limestone with continuous permafrost, in the Ogilvie Mountains, YT, it has been proposed that the last significant karstification of this area ended when permafrost conditions began to dominate (Lauriol and Clark, 1993). In continuous permafrost the development of karst in limestone and dolomite tends to be restricted to the active layer or

to scarp edges where the local hydraulic gradient is high, unless the situation is complicated by glacial inheritance.

2.7 GLACIATION AND KARST AND PERIGLACIAL PROCESSES

The effects of glaciation include the creation of depositional and erosional landforms, but in some rare cases there is no change in the pre-existing landscape. The effect of glaciation on karst is complex as it ranges from the complete destruction to the preservation of karst landscapes and from the prohibition of karst development after glaciation to its rapid development (Ford and Williams, 1989, p.473).

Ford and Williams (1989, p.475) define two types of glacial conditions, alpine and continental. Within the alpine glacial conditions there are two types of ice-karst relationships, the *Canadian type* and the *Pyrenean type* (Ford and Williams, 1989, p.475). The Canadian type exists where both the input and the output areas of the karst system are glaciated. When all of the topography is covered by the flowing ice, about 500-5000 m deep, then the glacial conditions are said to be continental. The Pyrenean type occurs where only the karst input areas are glaciated. This is explained by the elevation of the input and output; the input is at a higher elevation and so is glaciated but the meltwater flows underground to outputs which are in valleys at a lower elevation and, thus importantly, ice-free.

Ford and Williams (1989, p.477-482) have divided the karst landforms of glaciated areas into eight categories as shown in Table 2.1.

Table 2.1 Categories of karst landforms in glaciated terrains

Postglacial	1	Simple forms - independent of preceding glacial forms: many karren, collapse dolines.
	2	Suffosion dolines, many solution dolines, limestone pavements, etc. where the location or part of the form is determined by preceding glacial features.
Adapted glacial	3	Glacial grooves, scourholes, potholes, kettle holes, cirques, moraine-dammed valleys, etc. adapted to karstic drainage.
Subglacial and Glacier marginal	4	Normal karst landforms (e.g. solution shafts) occupying anomalous hydrological positions.
	5	Subglacial calcite precipitates; some arctic corridor karst?
Glaciated karst	6	Dolines, etc. subject to one apparent episode of glacial erosion and/or deposition.
Polygenetic forms	7	Most large closed karst depressions in glaciated terrains; created by repeated glacial and karst episodes.
Preglacial karst	8	Some relict caves. (Surface karst features are modified into types 6 or 7).

(Ford and Williams, 1989, p.477)

Types 1 and 2 proposed by Ford and Williams are postglacial karst features and are the easiest to categorize of all the forms in the above table. Category one karst features have developed since glaciation and are not effected by prior glacial events. Category two features often preferentially develop due to the effects of glaciation. For example, pavements readily develop on surfaces scoured by glacier action which left a smooth, nearly horizontal surface. Features found in category three include landforms that are the result of glacial processes but which have adapted their drainage to be characteristic of a karst terrain. Category four landforms developed during glaciation but presently are located at abnormal hydrological positions. An example of a category four landform is a doline that developed beneath the glacial ice but is now at a position incongruent with today's hydrology. Category five,

subglacial calcite precipitates are highly streamlined crusts deposited from the pressure melt film of subglacial flow as it refreezes. The only examples of these precipitates are unique to the carbonate rocks and the subglacial environment. In this same category is (some) arctic corridor karst which is hypothesized to have formed due to the dissolution by subglacial waters. Features in category six are rare as the landforms in this category were originally karst features that have been modified by glacial action during only one glacial episode. Most karst features subjected to glacial environments are included in category seven. In this category karst features have been modified more than once by glacial action and are polygenetic, multiphase features and the number of phases of modification is usually unknown. A large closed depression that was enlarged by glacial and karst processes and now drains karstically is an example of a landform in category seven. Category eight has few documented examples as it includes karst landforms that existed prior to glaciation and were not modified during the glacial period. Most pre-glacial karst landforms are included in category seven as they have been modified into polygenetic landforms.

During glaciation there were areas where either erosion or deposition were predominant depending on the conditions of the glacier and the underlying terrain. Therefore, karst landforms existing prior to glaciation at the edge of a zone of deposition probably were not infilled as greatly as landforms found further within the depositional area of the glacier. On the other hand, the karst features found in an erosional zone of the glacier would often be erased by the glacier and not preserved. Of course, after glaciation new karst features could be produced providing there was sufficient water and carbon dioxide in a carbonate area. The formation of new karst features may be aided, or controlled, by the residual glacier

landforms such as whalebacks or scoured/plucked surfaces. Again the opposite may also occur: the glacial debris covering a surface may inhibit the development of a karst landscape because water and carbon dioxide cannot act on the carbonate rock under the glacial debris. Therefore, the effects of glaciation on karst are varied and must be evaluated case by case.

Where permafrost is widespread or continuous and there is glacial inheritance, two conditions, other than the ones in Table 2.1, are common. The first is that drift cover completely contains the active layer or chemically shields the rock. The second is that the rock was bare and thus developed karren soon after glaciation ended but this was reduced to a felsenmeer, or shillow (rubble or rock debris). The second case is frequently observed in temperate environments where pavements form. This is also evident in some cold environments such as the Dodo karst southwest of Norman Wells, NWT. These two common conditions are extensive on the carbonate plains in the southern arctic islands as well as in the northern arctic islands of Canada (Ford, 1987). Remnant glacial features affect the result of present geomorphological processes, such as karst and periglacial. The history of landscape development in a glaciated area is interesting due to the added possibilities for expression of present processes; the Campbell Uplift has such a story.

2.8 CAMPBELL UPLIFT

The Campbell Uplift is about 11 km wide and 22 km long, elongated along a northeast, southwest axis. The major component of the uplift is bounded by Campbell Lake on the east, the East Channel of the Mackenzie River on the west, to the north by Dolomite Lake (locally called Airport Lake), and to the south by Gull Creek and Campbell River

(Figure 1.1). Just south of the Campbell Uplift is the Gwich'in Territorial Park. On the east side of Campbell Lake between the lake and the Dempster Highway is an outcrop of bedrock belonging to the Campbell Uplift. An outlier exists about 8-16 km to the southwest of the major structure and appears to be from the lower units of the Paleozoic bedrock succession (Dyke, 1975).

2.8.1 Geology

The Campbell Uplift is part of the Aklavik Arch lithostratigraphic complex. This is a northeast-trending tectonic element that is 600 km long stretching from the Canadian side of the Alaskan border to the Beaufort Shelf northeast of Tuktoyaktuk Peninsula (Young and Norris, 1978, p.5). The Aklavik Arch includes rocks ranging from the Proterozoic, late Precambrian, (seen in the Campbell Uplift) to the late Tertiary. The Campbell Uplift has a notable relief due to its structure. It is not a fault-bounded structure but is an elongated, dome-like feature which is hypothesized to be a structural high point on the Aklavik Arch. It is cut by many north-east trending vertical, curvilinear, longitudinal faults (Dyke, 1975; Norris and Calverley, 1978, p.58).

The geological time sequence for the area near Inuvik, NWT is shown in Figure 2.2. The uplift is composed of Proterozoic rocks of Helikian age, Pu, (1600-900 Ma, Upper Precambrian) (northwest Campbell Uplift (CU)), of Paleozoic rocks of Cambrian to Devonian age, CSv (middle and southwest CU), and of Lower and Middle Devonian aged rocks, DG, (northeast CU) (Figure 2.3). The latter two groups of rocks are further categorized as part of the Vunta (CSv) or Gossage (DG) Formations, both limestone and dolomite of marine

origin (Geology Map, 1517A).

The present form of the Campbell Uplift is thought to have developed dominantly in the early Tertiary through a series of processes including compression, relaxation, strike and slip faulting (Young, 1978). Campbell Lake occupies a graben floored by Cretaceous beds and flanked by Paleozoic exposures (Figure 2.3) (Ritchie, 1976). There are fluvial deposits, Q_{ff} , bordering Campbell Lake on both the east and west sides as well as a small patch between the Vunta formation and Precambrian rocks (KHR on map). These deposits obscure most bedrock but facilitate the growth of "lush" vegetation.

East and north of the Campbell Uplift is elevated terrain that is part of the transitional zone between muskeg and tundra. West and south of the Campbell Uplift is the Mackenzie Delta. This lowland area consists mainly of lakes, waterways, and muskeg at approximately sea level. This is in contrast to the scarp and valley features of the Uplift which rise to over 300 feet above sea level.

Era	Period		Ma	Notes
Cenozoic	Quaternary		5.3	Q _{ff} - fluviatile
	Tertiary		66.4	
Mesozoic	Cretaceous		144	KHR - Horton River formation
	Jurassic		208	
	Triassic		245	
Paleozoic	Permian		286	
	Carbon-iferous	Pennsylvanian	320	
		Mississippian	360	
	Devonian		408	DG - Gossage form.
	Silurian		438	CSv - Vunta formation
	Ordovician		505	
	Cambrian		570	
	Precambrian		4600	

Note: Ma - Million years ago

Figure 2.2: Geologic time sequence for the Campbell Uplift, NWT, including reference to geological units used on Geology of the Campbell Uplift map Figure 2.3.

Pu – Precambrian CSV – Vunta formation
 DG – Gossage formation
 KHR – Horton River formation Qff – fluvatile

Figure 2.3: Geology of the Campbell Uplift, Northwest Territories, Canada

2.8.2 Glacial History

The Campbell Uplift is located within the Quaternary glacial area of the northern Interior Plains area of Canada. This region includes the area between the Canadian Shield and the western Cordillera, including the western Arctic Islands (Figure 2.4). During the Quaternary period, the continental glaciers originating west of Hudson Bay repeatedly covered the northern Interior Plain (Vincent, 1989, p.100). This region is one which Quaternary glaciers advanced into, rather than originated from. Deposition of drift, therefore, is geomorphically more important, in general, than glacial erosion and the results are thick Quaternary successions (Vincent and Klassen, 1989, p.99).

The Campbell Uplift is within the limits of Late Wisconsinan (10 - 42 ka) Laurentide ice advance (Vincent, 1989, p.100-137; Dyke, 1990, p.9). The Uplift has two meltwater channels connecting Campbell and Dolomite Lakes that most likely formed during the Wisconsinan glaciation. There is much controversy over the glacial limits in the northern Interior Plains because this region is at the margin of the Laurentide ice sheet. Geologists agree that the glacial deposits in the area of the Campbell uplift are Wisconsinan although they do not agree on the actual ages of the deposits.

There are two views of when the furthest advance of the Laurentide ice sheet occurred in the northern Interior Plains area. Some Quaternary geologists contend that the maximum advance occurred in the Early Wisconsinan (42-30 ka) followed by less extensive advance in the Late Wisconsinan (15-10 ka) while others argue that the maximum advance occurred in the Late Wisconsinan and was then followed by a readvance. Both groups agree that the Wisconsinan glaciation did reach the Campbell Uplift but the timing of it is still very

controversial. It is still unknown if glaciers prior to the Wisconsin glacialiation have reached the Campbell Uplift and, if they did, how often and when.

Figure 2.4: Limits of the glacialiation during the Quaternary period in the northern Interior Plains area of Canada (after Vincent, 1989, p.106)

2.8.3 Climate and Vegetation

The climate of the Campbell Uplift is subarctic. Table 2.2 describes the main climate characteristics as recorded at the Inuvik Airport Weather Station, 68°18'N 133°29'W, 59m altitude, from 1957 to 1990 (Environment Canada, 1991). The measurements recorded at the Airport are a good approximation of the climate in the Campbell Uplift.

Table 2.2: Climate characteristics at Inuvik Airport, 1957-1990

Temperature	Mean (year): -9.5°C Maximum (summer): 19.5°C Minimum (winter): -33.7°C
Precipitation	Rainfall (June - August): 92.3mm Snowfall (yearly total): 175.2cm Precipitation (yearly total): 257.4mm
Wind	Speed (year): 10km/h Direction (most frequent - yearly average): East

The average frost free period in this area is 45 days (French, 1996, p.12). Autumn freeze-up of the East Channel of the Mackenzie River occurs quickly in the month of October and spring break-up generally occurs in May or June.

The Campbell Uplift is situated in the northern subarctic ecological region (Wahl *et al.*, 1987) and is characterised by hilly black spruce muskeg. The area lies close to the limit of the continuous boreal forest. Trees found in the Campbell Uplift include white spruce, black spruce, larch, birch, poplar, and aspen. Although there are patches that show evidence of fire they seem to be of limited extent. There are many bedrock outcrops ranging from only a few metres to several tens of metres in height but many of these rocks are covered in

patches of lichen and mosses. The Campbell Uplift is part of "Megaberingia"; a lowland area that was ice-free during the late Cenozoic (66 Ma - present) and acted as a refuge for plants. The Campbell Uplift is unique in that it has a full complement of arctic-alpine calciphiles including a number of species of the megaberingian range.

2.8.4 General Geomorphology

The geomorphology of the Campbell Uplift will be described in detail in Chapter 4, Results. It is characterised by periglacial features such as frost shattered and wedged rock and solifluction slopes. There is evidence of karst dissolution surfaces on many of the frost weathered surfaces. Pavements, karren, and sinks are some of the characteristic karst features of the study area. The glacial inheritance of the Campbell Uplift includes whalebacks and glacial drift covering many surfaces. The landforms of the Campbell Uplift are the result of various geomorphic processes which are discussed in Chapter 4, Results, and Chapter 5, Analysis.

CHAPTER 3: METHODOLOGY

3.1 SITE SELECTION

During a one day reconnaissance trip to the northeast part of the Campbell Uplift Dr. Lundberg observed several distinct karst features, including clint-and-grike pavements and cliff-sided box valleys, in this continuous permafrost region (Pers. Comm. Lundberg, 1997). Some features were partly obscured by frost debris indicating that at least two geomorphic processes were acting in the area, karst and periglacial. It was thought that the competition between karst and periglacial processes might be more extensive and that the rest of the Campbell Uplift would be similar. Therefore, the Campbell Uplift was selected as a site for further study to investigate i) the morphology of an arctic karst region, and ii) the potential competition between geomorphic processes within a permafrost zone in a carbonate rock. The Campbell Uplift is small in area and accessible by boat and foot from the town of Inuvik. Good coverage of most of the area is possible, making this a logistically feasible area to study.

3.1.1 Maps and Air Photographs

The Campbell Uplift is found on the following geologic and topographic maps:

1:250 000 - Aklavik - District of Mackenzie - Surficial Geology - Map 31 - 1979

1:250 000 - Aklavik - District of Mackenzie - Geology - Map 1517A - 1981

1:250 000 - Aklavik, District of Mackenzie, NWT - Ed. 3 - AKLAVIK 107B (1994)

- 1:50 000 - Inuvik, District of Mackenzie, Northwest Territories - Ed. 2 - INUVIK 107 B/7 (1994)
- 1:50 000 - Campbell Lake, District of Mackenzie, Northwest Territories - Provisional, Ed. 1 - 107 B/2 W (1957, Printed 1966)
- 1:50 000 - Campbell Lake, District of Mackenzie, Northwest Territories - Provisional, Ed. 1 - 107 B/2 E (1957, Printed 1966)

Air photographs of the Campbell Dolomite Uplift from the National Air Photo Library were used to choose accessible field sites and to identify geomorphological features (karst, periglacial, glacial) within the selected areas prior to the field work. The air photos used were taken August 1984, flight A26603, at 10 300 feet A.S.L. and are scaled at 1:20 000. Photos numbered: 91-93, 28-130, 139-149, 164-166, and 171 were used and were invaluable in mapping the landforms and sites as they show the features of the terrain more clearly and accurately than the topographic maps of the field area.

3.1.2 Field Site Assessment

Specific study areas were chosen within the larger Campbell Uplift using the following criteria. Only the areas which were underlain by Cambrian to Devonian age bedrock of the Gossage or Vunta formations were chosen as both of these formations are limestone and dolomite of marine origin (Geology - Map 1517A - 1981). The difference between the rock of these formations is based on time of deposition, during the Cambrian to the Devonian for the Vunta formation and during the Lower and Middle Devonian for the Gossage formation. Both formations are dolomite and limestone rocks of marine depositional environments which have similar characteristics and thus resemble each other in physical appearance. The lowlands, shown on the geology map as fluvial deposits of fans and fan aprons (silt, sand

and gravel, in part with cover of organic deposits) were not investigated because the hypothesis concerned the carbonate deposits in the Campbell Uplift. Although the lowlands are most likely underlain by carbonates, they have been covered by deep fluvial sediments and the carbonate landforms are completely masked. The areas relevant for this study are stipled on Figure 1.2.

The second criterion was accessibility. The field areas needed to be accessible from either Campbell Lake or Falcon Lake or by foot from the Dempster Highway (Figure 1.1). The area of study in the Campbell Uplift is bounded by faults and the cliffs presented potential obstacles that needed to be considered. Once in the field, it was evident that there were points where the cliffs could be climbed without personal danger. Therefore, the cliffs were not a large impediment to area selection. Only one area southwest of Campbell Lake (x on Figure 3.1) was difficult to access because of low water levels and terrain that is difficult to traverse on foot. Therefore, other than this area, all other relevant areas were studied.

The areas in the Uplift to be studied were named based on points of access or geographical location. The six field areas in the Campbell Uplift are:

1. Falcon Lake;
2. Bottom of Campbell Lake;
3. Middle of Campbell Lake, South Side;
4. Middle of Campbell Lake, North Side;
5. The Quarry; and
6. The Road

and are marked on Figure 3.1. As work progressed each field area was sub-divided into study sites which are indicated on the air photographs in Chapter 4, Results, Figures 4.43-48.

Figure 3.1: Map of study areas within the Campbell Uplift, N.W.T.

3.2 FIELD METHOD

The field work was undertaken in July and August of 1998 when there was no snow cover in the study area and the water levels were high enough that the field areas were accessible by boat. Data were collected through field mapping, surveying within the sites, and rock sampling within the six field areas.

The field method was developed during the field work and was an adaptive process which depended on what was discovered in the field. A) The field sites were determined while in the Campbell Uplift, B) the surveying techniques were adapted to the geomorphological features in the field so that an encompassing representation of each field site could be compiled, and C) location of rock samples were decided in the field depending on what landforms were found as the geological map was not detailed enough for this. These three components of the field method are described below.

A) For each field area a few days were used for reconnaissance to identify the geomorphological features of the area. At this time the features were categorized in a table with field sites corresponding to those marked on the air photographs (Figures 4.43–48), and the majority of the survey and rock sampling sites within an area were chosen.

B) Once the locations of the features were established they were described and measured to document the geomorphology of the Campbell Uplift. The landforms of an area were determined, several were surveyed, and then a type example for each landform chosen. It was most useful to describe in detail one example of a landform which was well developed, distinct, and thought to be formed by one dominant process. This provided a clear picture of the simple landforms which aided in the recognition and documentation of complex forms.

Notes were made of the varied locations of other examples of the same landform but measurements of the same feature elsewhere were quickly estimated due to time constraints. This method of using type examples is based on the type section idea used in geological studies and is more useful than describing randomly chosen landforms which do not necessarily best exemplify the study area.

C) The final task was to collect rock samples to determine if lithological variation was indeed a filter in the Campbell Uplift. Specimens of the bedrock were taken at the field sites for analysis later. Hand specimens, 5 to 10 centimetres in size, were taken where surface morphology (landform or feature) changed, where there was a visual change in the bedrock colour, texture or grain size, and at new study areas.

3.2.1 Surveying

The majority of geomorphological features can be described using a plan view and one or more cross-sectional profiles, at right angles to the grain if the feature is linear, and from several angles if the feature is non-linear. For this study, the air photos provided the plan view of the bigger features and photographs and / or field sketches were made of the smaller features. The details are presented in Chapter 4, Results.

Line transects were completed in each field area. This served to describe and to document landforms morphometrically, to detect landform variations, and enable comparison of the landforms. This technique has been used in several other studies: eg, in Lundberg (1977), tower karsts of Chillagoe, Australia, were documented using line transects to document slope forms on different rock types. Akagi (1980) studied the relation between

slope profiles and rock type in Arizona by using traverses to document appropriate characteristics. The geomorphology of the Napier Range in Western Australia was studied by Goudie *et al.* (1990) and they surveyed transects in order to collect data on slope type and for rock mass classification. Finally, Young (1960) is referenced for his valley profiles in three locations in Britain to determine the importance of slope characteristics, specifically slope angle. Line transects were useful as a basis for data collection in the Campbell Uplift, NWT, as they provided a framework with which to work. Due to the large study area, this method served to focus the search for landforms instead of merely haphazardly recording observed features.

The transects varied in length depending on the terrain, ending usually in extended vegetated slopes to either side of the outcropping carbonate rock landforms. The transects averaged 114 metres in length, the shortest was 31.5 m and the longest was 243.4 m. Since the landscape is generally strongly lineated, the choice of transect direction was at right angles to the lineation. The number of transects for each area varied from two to six and depended on the complexity of the landforms, lithological variation, and transect lengths.

The distance (measured with a cloth tape) and angle of inclination (measured with a Sunto clinometer) for each leg of the transect comprise the base information for each line transect. These methods are based on the survey methods described by Pitty (1969) and Young *et al.* (1974). Details of the slope form were drawn by hand onto the line of each leg. Lithological, glacial, periglacial and karstic features were noted along the transects (see Appendix A). Any unique feature was described in detail while at the specific field site. The more common features were described once in a type section and subsequently only noted as

existing on other line transects.

Lithological features noted in the transect data include bedding, or lack of, fracturing and jointing of the rock, and grain size. Some of the geomorphological features recorded in the transect data included glacial grooves, whalebacks, scoured or plucked surfaces, pavement, surface dissolution and precipitation, sinks, undercutting of bedrock, evidence of frost shattering and wedging, frost pockets, and solifluction surfaces. Description of the lithological and geomorphological features on the transects is found in Chapter 4, Results.

The features noted on the transects are representative both of the features on the transect line and of the features that lie perpendicular to the transect line. For example, if a cliff face with many frost pockets is perpendicular to the transect line then a frost pocket is included in the data even if a frost pocket did not lie precisely on the transect line. Because time constraints limited the number of transects, it was decided that this method of including features representative of the terrain perpendicular to the transect line would create a sufficiently encompassing view of the landforms and features of the field sites. Since this study does not focus on only one landform (for example only dolines) but on the documentation of all landforms that exist in the field areas, this method was deemed a sufficient means to achieve the goal. Based on the relationships presented in the landscape development model, it was anticipated that the processes acting at the sites and the role of filters could be determined with the type and quantity of data collected.

3.3 TREATMENT OF SURVEY DATA

The length and angle of the slopes as recorded in the line transect data were entered into a spreadsheet, along with relevant field notes. The transect stations were graphed and the segments between the points hand-drawn. This generated the most representative depiction of the landscape. Since the segments between the data points are not computer drawn straight lines but included some of the morphologic features such as undercutting, curved slopes and vertical sections of the slopes, the transect graphs are a good indication of the landscape.

Not all the landform data were associated with a line transect but these data were not discarded. All landforms and unique features were documented in the field data and are presented in Appendix A. An enormous quantity of data was collected from the line transects. The aim of this thesis is to document existing landforms. This was done using some of the transect information. Another aim of this work is to provide baseline data for future geomorphologists. As such, not all of the data gathered in this study are used herein as they are intended for comparison by researchers in the future. Therefore, the line transect data are not used to the fullest and are presented to create a data source for future studies in geomorphology.

Locations of the landforms were entered in a table that includes all the landforms documented in the Campbell Uplift and from which the frequency of sites where a landform was located could be summed. Typical dimensions of specific landforms were determined by averaging the dimensions recorded in the field notes.

3.4 ROCK SAMPLES

A rough classification scheme was used in the field based on the hand specimens and the characteristics of the environment from where they were taken. The rocks taken from the field were divided based on the hand specimens into lithological groups according to Sibley and Gregg (1987) and Dunham (1962). A representative sample was selected from each of the fourteen groups determined. For each representative sample percent insoluble residue was determined, and a thin section was made (by the Department of Geology Thin Section Lab at Carleton University). Thin sections were made to examine the small-scale properties of the rock. Lithological characteristics include crystal size distribution, crystal boundary shape, allochemical components, and matrix characteristics. The thin sections were stained using an Alizarin Red S and potassium ferrocyanide mixture (Dickson, 1966) to determine the relative iron to magnesium content and whether the rocks, or specific parts thereof, were dolomite or calcite (limestone). These techniques were used to determine the lithological variations between the rock groups so that analysis of the relation between lithology and landform could be performed.

The rock types were mapped on the air photographs according to the 14 lithological groups. As with the landform data, the groups were assigned a code which was then marked on the air photographs at the appropriate field sites in the six field areas. Field notes recorded similar rock types as decided by hand specimen analysis in the field and the rock characteristics were noted. Thus, every field site and distinct landform has an associated rock type.

3.5 DATA ANALYSIS AND HYPOTHESIS TESTING

The landform and lithological data were combined into one table for each site. The landforms were divided into types: glacial, periglacial, karst and complex landforms. The lithological groups, as defined by the hand specimens, and specific landform types were compared. Each landform has an associated lithological group (or groups) which each has specific properties. For each landform the frequency of each lithological group was recorded. The percentage of each lithological characteristic (such as insoluble content, inhomogeneity, etc.) was calculated and the properties most often represented were highlighted. For example, solifluction lobes were recorded in six locations in the Campbell Uplift and were represented by three lithological groups, A, B, and M. The lithological groups were not evenly represented; A and M were the lithologies at only one site each whereas B was the rock type at four sites. Therefore, even though A and M have an insoluble content of less than 10% and only B is between 10 and 20%, the most common insoluble content for solifluction lobes is medium, between 10 and 20%, as two thirds of the solifluction lobes have this characteristic. The majority of the solifluction lobes (5 of the 6 samples) are on iron free dolomite as both lithological groups A and B are this type of rock. The other rock characteristics are similarly analysed. This method was adopted to address the question of whether the presence of a landform is related to a specific lithology and, thus, a specific lithological characteristic. If no relationship was determined then a second question of whether certain characteristics of a landform, such as slope form, are related to a specific lithology was asked and more analysis completed. For example, steepness of slope of all whaleback forms was used to identify possible rock characteristics that are associated with

steep or non-steep slopes.

The landforms in general and lithology were analyzed for relationships and documented where these exist. The four different categories of landforms, karst, periglacial, glacial, and complex, were addressed in the same manner as individual landforms to determine the most prevalent characteristics of these types of landforms. The location of the landforms was noted and the frequency of occurrence of the landform in specific study areas was compared with the total number of the specific landform documented throughout the Campbell Uplift. The landform-controlling lithological properties were determined to be the properties related to a specific landform or type in the majority of the comparisons. The theory is that the more often a lithological characteristic is noted for a specific landform or type of landform (process specific) the more likely this property will be a significant predictor of the landform or process.

The landscape development model was applied to the Campbell Uplift using the collected data and the above analysis. The model is most importantly applied to the landform groups based on process and is shown in Chapter 5.

CHAPTER 4: RESULTS

4.1 INTRODUCTION

This chapter presents a detailed account of each lithology and landform documented in the Campbell Uplift. It includes specific information about the study areas and describes the type examples. Features are illustrated by sketches or the best photographs available. The photographs are not necessarily of the type example but those which show best the features discussed.

This chapter begins by describing the lithology of the Campbell Uplift. The macro- and microscale properties of the rock samples from each of the fourteen groups are presented in tabular form. The lithological variations of the landforms in the different study areas are discussed in Chapter 5, Analysis.

The geomorphology of the Campbell Uplift is examined next. It is categorized according to geomorphological process: karst, periglacial, glacial, and a combination of two or three of these processes. A summary of observations of the Campbell Uplift, including landform description, location, and prevalence, is presented together with background information to see if the landforms in the study area are consistent with those described in the literature. The descriptions of the landforms found in the Campbell Uplift are presented to document the features and to provide a data base of the landforms, particularly of the karst.

The final section of this chapter (4.7) examines the spatial variation of landforms and lithology. Locations of the landforms and lithologies are presented to begin to address the

question of whether lithology is a form-controlling filter in the Campbell Uplift. Analysis of the data presented in this chapter is presented in Chapter 5, Analysis, and the results are applied to the Landscape Development Model in Chapter 6, Summary and Conclusions.

4.2 LITHOLOGY

Microscopic lithological characteristics include both macro- and micro-scale properties. Macro-scale lithological properties include bedding (or lack thereof), grain size, and other visual characteristics. Micro-scale properties include crystal shape, size, orientation, packing (Blatt *et al.*, 1980, p.9-10) and boundary conditions of the crystals.

4.2.1 Description of the Macro-scale Rock Properties

The rock sampled in the Campbell Uplift is Cambrian to Devonian limestone and dolomite of marine origin. The rocks from the field areas at Falcon Lake, the Bottom of Campbell Lake, and both the South and North Side of the Middle of Campbell Lake are of Cambrian to Devonian age and from the Vunta Formation (Geology Map, 1517A). The Quarry and Road field areas are composed of rock from the Gossage Formation of Lower to Middle Devonian age (Geology Map, 1517A). Since in the field there is no visible difference in the formations, five of the fourteen lithological groups have rocks from both formations whereas the other nine groups have samples from only one formation.

The lithology of the Campbell Uplift was determined from field observations and laboratory analysis of samples. The rocks in the Uplift were identified in the field by their bedding characteristics, Figures 4.1 and 4.2, their relative grain size, vugginess (Figure 4.3),

'impurities', colour, and visible calcite (Figure 4.4). Table 4.1 describes the rock types observed in the field and their associated formations.

Figure 4.1: Example of thin and thick bedding in the Campbell Uplift (thin bedding is thinner than 0.5 m; thick bedding is greater than 1 m)

Figure 4.2: Example of massive bedding in the Campbell Uplift

Figure 4.3: Example of vuggy rock

Figure 4.4: Example of visible calcite

Table 4.1: Macro-scale properties of the rock in the Campbell Uplift

Lithology Group	Formation	Grain Size	Inhomogeneity
A	CSV	coarse	inhomogeneous
B	CSV	coarse	inhomogeneous
C	DG	medium	homogeneous
D	CSV	med-fine	homogeneous
E	CSV	med-fine	inhomogeneous
F	CSV	fine	homogeneous
G	CSV and DG	fine	homogeneous
I	CSV and DG	fine	homogeneous
J	CSV	fine	homogeneous
K	DG	fine	inhomogeneous
L	CSV	fine	homogeneous
M	CSV and DG	very fine	inhomogeneous
N	CSV and DG	very fine	inhomogeneous
O	CSV and DG	very fine	homogeneous

N.B. Formation is either the Vunta formation (CSV) or the Gossage (DG)

Grain size is: coarse, 2-1mm; medium, 1-0.6mm; medium-fine, 0.6-0.2mm;
fine, 0.2-0.02mm; and very fine, 0.02 and smaller

4.2.2 Description of the Micro-scale Rock Properties

Limestone and dolomite are the two major rock types in the Campbell Uplift study area. Limestone is presented first because dolomite is usually diagenetically altered limestone.

4.2.2.1 Limestone

Figure 4.5 depicts Dunham's (1962) classification scheme which was used to describe the limestone, CaCO_3 , from the study area.

Depositional texture recognizable					Depositional texture not recognizable
Original components not bound together during deposition				Original components were bound together	
Contains mud (clay and fine silt-size carbonate)			Lacks mud and is grain supported		
Mud-supported		Grain-supported			
Less than 10% grains	More than 10% grains				
Mudstone	Wackestone	Packstone	Grainstone	Boundstone	Crystalline

Figure 4.5: Limestone classification scheme (after Dunham, 1962)

Dunham based this classification scheme on the textural maturity (fabric) of the limestone, which is related to the energy level of the environment present at the time of limestone deposition (Tucker and Wright, 1990, p.18) and the presence of biological binding. A limestone deposited in a low energy environment would have less grain production. For example, a mudstone is most likely to be formed in a low-energy depositional environment whereas a grainstone or boundstone would be formed in a high-energy environment.

4.2.2.2 Dolomite

Figure 4.6 describes the classification of dolomite, $\text{CaMg}(\text{CO}_3)_2$, according to rock texture including crystal size distribution and boundary shape (Sibley and Gregg, 1987). The classification is depicted in the flow chart, Figure 4.6.

Figure 4.6: Dolomite classification scheme (after Sibley and Gregg, 1987, p.968)

Crystal size distribution is either unimodal or polymodal and is determined by qualitative or quantitative analysis of a thin section. Boundary shape is either nonplanar, planar-e (euhedral), or planar-s (subhedral) as depicted in Figure 4.7 (Sibley and Gregg, 1987, p.969).

One can interpret the mechanisms of dolomite nucleation and growth from this classification scheme. According to Sibley and Gregg, unimodality indicates "a single nucleation event on a unimodal substrate" whereas polymodality indicates "multiple nucleation events on a unimodal or polymodal substrate or differential nucleation on an originally polymodal substrate" (Sibley and Gregg, 1987, p.967). Boundary shape indicates

Nonplanar: closely packed anhedral crystals with mostly curved, lobate, serrated, or otherwise irregular intercrystalline boundaries.
Planar-e (euhedral): most dolomite crystals are euhedral rhombs; crystal supported with intercrystalline area filled by another mineral.
Planar-s (subhedral): most dolomite crystals are subhedral to anhedral with straight, compromise boundaries and many crystal-face junctions.

Figure 4.7: Planar and nonplanar examples and descriptions of dolomite (after Sibley and Gregg, 1987, p.969)

the mechanisms that characterize crystal growth. Nonplanar boundary shape is characteristic of crystal growth at temperatures greater than 50°C and/or at high supersaturation, and of nonfaceted crystal growth. Planar boundaries are the result of faceted growth. "Both planar and nonplanar dolomite can form as a cement, replacement of CaCO_3 , or neomorphism of a precursor dolomite" (Sibley and Gregg, 1987, p.967). Although it is often difficult to distinguish between true dolomite cement and precursor cement, "any pore-filling dolomite that did not replace a precursor pore-filling material" (Sibley, 1982, p.1088) is a dolomite cement.

4.2.2.3 Description of the Rocks

The 55 rock samples collected from the Campbell Uplift were divided into fourteen groups based on the handspecimen (Section 3.4). Tables 4.2 and 4.3 describe the micro-scale

properties of each rock type. The thin sections of each rock type were stained to estimate the composition of the rock. Alizarin Red S with potassium ferrocyanide (Dickson, 1966) was used to differentiate calcite and dolomite and their iron contents. The results are presented in Tables 4.2 and 4.3 in the column under the heading 'Limestone' or 'Dolomite'. The limestone samples included mudstones, wackestones, packstones, and grainstones with different amounts of bioclasts. The dolomite rock samples were both iron free and ferroan, polymodal and unimodal, and planar and nonplanar. Following the tabular information are photographs of a representative handspecimen for limestone (Figure 4.8), iron free dolomite (Figure 4.9), and ferroan dolomite (Figure 4.10).

Figure 4.8: Handspecimen of a mudstone limestone from the Middle of Campbell Lake - North Side field area, Vunta formation

Table 4.2: Microscale properties of the limestone in the Campbell Uplift

Type	Percent (%) Insolubility	Limestone	"x"-stone (Matrix)	Bioclast Description	Comments
M	7.2%	limestone	packstone	40% bioclasts	- crynoids and gastropods - normal marine peoloidy
N	8.9%	limestone	mudstone	limited bioclasts	- patchy dolomite along stylolites - calcite to dolomite
O	10.7%	limestone	fossiliferous mudstone	bioclasts 385-462µm round	- round(1) bioclasts sometimes filled with quartz?chert? - one large bioclast(4158µm x 5698µm) with 3 bioclasts
L	11.2%	limestone	packstone	bioclasts	- chert - quartz
K	20.4%	dolomitic limestone	grainstone	nonplanar-a dolomite clasts bioclasts	- bivalves - chert - packstone - lithoclasts
C	26.6%	limestone	mudstone (coral)		

Table 4.3: Microscale properties of the dolomite in the Campbell Uplift

Type	Percent (%) Insolubility	Dolomite	Host Rock: Modality, Size	Planar or Nonplanar	Comments
F	5.3%	dolomite (Fe ²⁺ -free)	polymodal crystals 77-616µm	planar-s and e (sub- and euohedral)	- 10% euohedral crystals filled with Ca
A	7.5%	dolomite (Fe ²⁺ -free)	polymodal crystals 120-200µm	planar-e (euohedral)	- vugs - Ca filling pore space and bitchem lining pore space - unstained to eye but lots of Ca "dots" 8µm x 16µm
B	11.2%	dolomite (Fe ²⁺ -free)	polymodal crystals 1155-1925µm	nonplanar-a (anhedral)	- Ca starting to fill pore spaces - unstained (no small Ca "dots" as in A)
E	11.8%	dolomite (Fe ²⁺ -free)	unimodal crystals 210µm	planar-s (subhedral)	- Ca starting to fill "pore" spaces, joints, and veins or replacing dolomite (dedolomitization starting) - ghosts of bioclasts, quartz clast, saddle dolomite
I	8.1%	ferroan dolomite	polymodal crystals	nonplanar-a (anhedral)	- Ca
D	8.8%	ferroan dolomite	polymodal crystals 385-770µm	planar-s (subhedral)	- unstained, no Ca - petroleum
G	10.5%	ferroan dolomite	unimodal crystals 24-48µm	nonplanar-a (anhedral)	- no Ca but uniform, crystalline strutures - veins are different - crynoid
J	24.3%	ferroan dolomite	polymodal crystals 25-320µm	nonplanar-a (anhedral)	- bedding - organic rich - calcitic

Figure 4.9: Handspecimen of an iron-free dolomite from the Falcon Lake field area, Vunta formation

Figure 4.10: Handspecimen of a ferroan dolomite from the Bottom of Campbell Lake field area, Vunta formation

4.3 KARST LANDFORMS

Karst landforms are the result of dissolution of soluble rock and the effects of this dissolution on and below the surface. Section 4.3.1 describes how general dissolution modifies rock surfaces and creates different types of karren which can eventually develop into larger features such as grikes. Pavements, of which grikes are a component, are described in section 4.3.2. Section 4.3.3 describes larger scale karst features including bogaz, corridor karst, and pinnacle karst in talus slopes. Karst depressions including dolines, stream sinks, and collapse features are presented in section 4.3.4. Calcite precipitation is discussed in the final section, 4.3.5, and is an indirect result of dissolution.

4.3.1 Surface Dissolution - Karren

A carbonate surface dissolves by the chemical reactions as described in Chapter 2. Dissolution creates indentations in the rock surfaces in circular or linear forms or a composite form of these two, generally termed "karren".

Surface dissolution occurs when unsaturated water passes over soluble rock in the presence of carbon dioxide. As the rock dissolves the solutes are carried away by flowing water. Different dissolutional surfaces will result depending on the intensity, duration, and saturation of the flowing water, among other variables. These surface are also affected by the presence or absence of soil and vegetation, impurities in the rock, superficial deposits, and lithology. If the surface dissolution features are less than about 1 cm then these features are called "microkarren". However, if the features are larger than 1 cm and less than about 10 m then the features are called "karren" and are subdivided depending on the surface

expression of the dissolution. Assemblages of individual karren may cover large areas, in which case they are called "karrenfeld" (Ford and Williams, 1989, p.375).

Figure 4.11 shows an example of typical dissolution on the surface of a piece of talus block in the Campbell Uplift.

Figure 4.11: Typical dissolution on the surface of a talus block in the Campbell Uplift

4.3.1.1 Microkarren

The morphological classification of karren will be used instead of the genetic classification because, as Ford and Williams (1989, p.375) point out, the genesis of some karren are still not understood well enough to classify all karren on a genetic basis. The smallest type of karren is microkarren. It can be either circular pan or linear in form. The form of karren is related to the impact of lithological control and gravitational control on the flow of water over rock. For example, linear features might result from either water flow controlled by gravity or by linear lithological features that guide the direction of the water's flow. On the other hand, circular karren might develop due to lithological characteristics, or biogenic activity, but with no gravitational control.

Most of the microkarren observed in the Campbell Uplift were a polygenetic combination of these two forms, resulting in oval shaped indentations in the rock surfaces. Microkarren in the study area were found on vertical to horizontal surfaces with the horizontal surfaces tending towards circular pan forms and the vertical surfaces towards the more linear forms indicating the influence of gravity. The surfaces were referred to as dissolutional surfaces in recording the field data. Dissolutional surfaces were observed in all the field sites on different types of rock surface, from rock fragments to large rock outcrops. They are not indicated on the air photographs due to their extensive coverage.

The type example of microkarren in the Campbell Uplift is a surface approximately 40 cm by 20 cm that is completely modified by dissolution. The dissolution has created small indentations which are 0.4 to 1.8 cm at their longest cross-section. The microkarren are not specifically round or oval but accentuate the small-scale properties of the rock, especially

grain size and shape.

4.3.1.2 Linear-form Karren - Cockling

The simplest form of linear karren is rillenkarren or 'solution flutes' (Jennings, 1985, p.75). These do not form in the field area, but a related form called "cockling", usually resulting from the degeneration of rillenkarren on steep slopes, occurs here. Rillenkarren develop preferentially on pure and homogeneous rock (Goudie *et al.*, 1990). Rainfall runoff is the dominant water source for rillenkarren formation. They form at the crest of a slope and decrease in depth further down slope and are approximately 1 - 3 cm wide. It becomes cockling if the hydraulically controlled rillenkarren are unable to maintain their typical channel appearance. Cockling is "a mixture of scallops, fluted scallops or ripples, and discontinuous rills" (Ford and Williams, 1989, p.385). Well developed cockling resembles the negative effect of regularly spaced cobble stones or a large number of miniature ice cube trays. The cockle effect is due to the inability of water to remain attached to the rock over which it flows and often occurs where lithological inhomogeneity causes a separation of flow. True cockling occurs only on very steep to overhanging walls but it is difficult to differentiate between simple etched out surfaces and true cockling. Rillenkarren, and therefore cockling, are the result of rainfall, and sometimes splash, or spray.

Cockling in the Campbell Uplift is about 1 cm in diameter as shown in Figure 4.12. As widths of rillenkarren channels are usually between 1.0 cm and 2.5 cm to 4 cm (Ford and Williams, 1989, p.385; Jennings, 1985, p.75) the Campbell Uplift cockling is small but not unusual in size. It is found on many different surfaces including cliff faces and outcrops as

well as some near-horizontal surfaces. Horizontal cockling is attributed, by the author, to light rainfall of short duration that does not travel a great deal upon reaching the surface. Cockling in the Campbell Uplift is evident to some extent in all field areas although it is documented most often on surfaces in the Falcon Lake field area.

The type example of cockling in the Campbell Uplift is a network of small oval indentations on a rock outcrop that is 75° from the horizontal. The indentations are only 0.5 to 1.5 cm wide, long, and deep. The network covers a surface area of approximately 0.25 m².

Figure 4.12: Example of cockling in the Campbell Uplift
(precipitate is not characteristic of most cockling in the Campbell Uplift)

4.3.1.3 Linear-form Karren - Splitkarren

Linear form karren are fissure controlled. Splitkarren are "depressions that are elongated along minor joints, veins, stylolites, or micro-fractures" (Ford and Williams, 1989, p.380). They are generally a few centimetres to several metres in length, have a length to width ratio greater than 3:1, and their depth is usually less than their length (Ford and Williams, 1989, p.380). The term splitkarren is derived from the fact that these karren look as though they are splitting the rock as the width usually tapers off with depth. "Closed splitkarren terminate on the host fissure. Open split karren terminate at one or both ends in other karren (e.g. a grike)" (Ford and Williams, 1989, p.380).

Splitkarren (Figure 4.13) are found in 21 of the 57 field sites (37%) in the Campbell Uplift, predominantly in the Vunta Formation rocks. The characteristic splitkarren in this area have a higher length to width ratio than those documented in the literature. This is likely due to the relatively short time (only since Wisconsinan glaciation) available for widening of the splitkarren and the slow speed of dissolution in an Arctic environment that has caused this ratio to be different than at other field sites documented in the literature. The splitkarren type example is nearly linear although it does have an irregular width. The type example is 20 cm long, only 3 to 5 cm wide (depending where width is measured along the surface), and tapers to depths of approximately 10 cm (again depending on where the depth is measured).

Figure 4.13: Example of splitkarren in a shallow-free pavement
(tape measure in centimetres, large increments are 10 cm)

4.3.1.4 Linear-form Karren - Grikes

Grikes, also called kluftkarren, are "the master karren features in most karren assemblages" (Ford and Williams, 1989, p.382). Grikes develop by dissolution along major joints or faults and are the principal drains of the karst water-system (Jennings, 1985, p.78; Williams, 1966). The water drains to the deeper epikarst, to dolines, or it can also drain to surface hydrological systems such as streams and rivers. Due to their development along joints, grikes tend to intersect at 60° , 90° , and 120° angles. Usually grikes are 1 to 10 m in length, 1 cm to 1 m in width at the top of the grike and taper with depth (Ford and Williams, 1989, p.382, Jennings, 1985, p.78). Grike depths are not usually greater than a few metres.

The blocks isolated between grikes are called "clints" or "flachkarren" and they can be host to other types of karren.

In the Campbell Uplift grikes are part of the examples of pavements as shown in Figure 4.14. There are two populations of grikes in the study area. The first type example in the Campbell Uplift is 50 cm long, 3 cm wide (tapering at depth), approximately 20 cm deep and basically linear. These grikes are generally not filled with soil or glacial debris although they do tend to have patches in which small mosses and lichen have grown in a clump. It is very difficult to see or feel inside the grikes but the type example seemed to have smooth sides. These grikes are associated with pavements and are found at three field areas in the Vunta Formation and one area in the Gossage Formation for a total of 15 sites (26% of the Campbell Uplift field sites).

There are only a few examples of the second population of grikes in the Campbell Uplift which are extraordinarily large grikes thought to be the older of the two populations due to their relatively large size. These grikes are located specifically at site 3 at the Bottom of Campbell Lake, and sites 1 and E, Middle of Campbell Lake - North Side. The dimensions of these grikes were, respectively: 2.4 m deep, 0.2 m wide; 2.5 m deep, 0.3 to 0.55 m wide, and 4 m deep and 0.3 to 0.5 m wide. These grikes have an average depth of 3 m and width of 0.4 m. A sketch of a large grike shows both the plan and cross-sectional views in Figure 4.15 and a different grike is shown in Figure 4.16. These large grikes all have soil packed on their floor which appears to be a mix of glacial debris and soil similar to the surrounding area. The soil may also contain a small amount of insoluble remnants from bedrock dissolution but no tests were completed in the field. The soil is at least several tens of centimetres thick,

which is thicker than that covering rock in surrounding areas.

Figure 4.14: Example of a small grikes in shillow-free pavement

Like the splitkarren, a characteristic grike (first population mentioned) in the Campbell Uplift is smaller than the "normal" grike cited in the classic literature from England and Ireland which have milder, wetter climates than the Campbell Uplift. Goldie (1973) cites the average widths of grikes in northwest England to be 18-20 cm while Williams (1966) measures the average widths of grikes in western Ireland to be 6 to 12 inches (15-30 cm). In Lundberg and Ford (1994), the grikes measured in the Dodo region (NWT) are from two populations in an arid, cold environment. The average widths reported from this area are 3.9 cm and 6.2 cm, thus the width of 3 cm in the Campbell Uplift is consistent with the

measurement of the smaller population in the Dodo area.

Figure 4.15: Sketch of a large grike with both plan and cross-section views

Figure 4.16: Example of a large grike in the Campbell Uplift

4.3.2 Pavements

Pavements are horizontal or near-horizontal assemblages of karren with regular patterns of clints and grikes (Ford and Williams, 1989, p.389). Karst pavements resemble artificial paving stones and are sometimes called limestone pavements, although they can develop on dolomite and even on some bedded sandstones and quartzites (Ford and Williams, 1989, p.389). The general term "dissolutional pavements" prevents confusion. Pavements are usually horizontal (or nearly) and are the result of some type of scour. Often the scouring is done by glacial action but in arid tropical areas the scour could be the result of parallel slope retreat. Pavements tend to develop on massively bedded rock and the dissolution

creating this feature can occur if the rock is covered by soil or not. Residual blocks, clints, are typically 1 - 10 m² and are bounded by grikes (Ford and Williams, 1989, p.382).

Pavements tend to form on mechanically competent rocks, on massively bedded rock, on compact or on pure rocks (Williams, 1966). According to Williams, "... beds which are thick, infrequently jointed and compact are better suited to support pavements than those which are thin, well jointed and imperfectly cemented" (Williams, 1966, p.162-3). Since pavements generally develop on bedding plane surfaces they, therefore, exist parallel to bedding-planes and the direction and angle of dip are important in their development.

Pavements develop ideally when the dip is 0° and are classified as 'horizontal' pavements. If the dip is less than 45°, 'inclined' pavements are likely to develop. If the bedding is arched in a dome shape resulting pavements are classified as 'arched'. No pavement develops if the dip is greater than 45° (Williams, 1966). Notable is the case in which pavements form down slopes prepared by glacial plucking producing 'stepped' pavements called 'schichttreppenkarst' (Williams, 1966). Although schichttreppen karst is well displayed in the Dodo region (Lundberg and Ford, 1994) no examples were noted in the Campbell Uplift.

If bedding is of thin to medium thickness then the clints are often subjected to mechanical weathering such as frost shattering and wedging as well as root wedging and even fire (Ford and Williams, 1989, p.389). The mechanical breakdown of the clints leads to a cover of rock fragments, called shillow, on the pavement surfaces. The shillow must be removed for pavement to continue to develop in deeper beds. The principal agent that removes this shillow in North America is scouring by glaciers in the Quaternary.

Most of the pavements observed in the Campbell Uplift can be classified as horizontal to inclined pavements as they have a dip of 3-20°. They are divided into two categories: 1) well developed pavements which are not greatly affected by frost action, although they have a small part of the pavement covered in frost shattered debris; and, 2) shillow covered pavements which are covered in the majority by frost shattered or wedged debris.

The type example of well developed pavements in the study area covers an area 4.2 m by 5.5 m, has a slope of 4°, and has karren covering 15% of the surface. The clints of the type example are one metre by one metre and are divided by the first population of grikes described earlier (Section 4.3.1.4). There is vegetation growing on approximately 5% of the pavement surface, predominantly around the edge (but not the cliff edge). The clints of this pavement are also dissected by splitkarren instead of grikes in some places. It appears that the splitkarren have combined together in some places to form grikes. There are also clints in the Campbell Uplift that describe the second type example of pavements. Together these clints cover a similar surface area as the first type example of pavements but individually the clints are smaller. These clints are narrow, about 0.35 m, and only half a metre long. They are divided by grikes that are well developed and distinguishable although there is also evidence of splitkarren and surface dissolution which comprises less than half the coverage of the grikes).

The type example of shillow covered pavement is larger, 25 m by 40 m, but the edges are harder to differentiate due to the encroaching vegetation. There are glacial deposits on the surface as well as some vegetation cover. There are no noticable surface karren present as 90% of the pavement is covered by frost shattered debris. This debris is 3 to 10 cm long

although the majority of the fragments are quite small, 3 cm by 2 cm by 1 cm. Approximately half of the fragments show evidence of dissolution.

A large number of well developed pavements (6 of a total of 17 examples) are found in the Falcon Lake, Vunta Formation, area whereas the shillow covered pavements are predominantly located in the Gossage Formation (6 of a total of 10 examples). Figures 4.14 and 4.17, show examples of well developed, shillow-free pavements, and Figures 4.18 and 4.19 show examples of shillow covered pavements.

Figure 4.17: Example of shillow-free pavement with grikes and splitkarren

Figure 4.18: Close-up of shallow covered pavement with small frost shattered debris

Figure 4.19: Example of large shillow covered pavement with frost shattered debris and glacial deposits

4.3.3 Large Karst Features Related to Grikes and Pavements

Small and large scale karst features can exist together to form a karst landscape. Karren are often found on larger features such as the walls of grikes or bogaz, an even larger forms of grike than previously described. Large grikes do not necessarily exist in isolation and many of these large features present in one area may contribute to the formation of a "giant grikeland", "corridor" or "labyrinth" karst, for example, the Queensland karst of Australia (Gale *et al.*, 1997). Pinnacle karst is usually formed due to a drop in the hydrological baselevel to form a landscape dotted with karst peaks. These larger karst features are described below.

4.3.3.1 Bogaz, Giant Grikelands, Corridor and Labyrinth Karst

A large grike, about 3 m wide and 10 m deep, can be called a bogaz, as defined by Cvijić in 1893, or a corridor, as described by Jennings and Sweeting (1963). 'Box valleys' and 'platea' are, respectively, square valleys and closed depressions which are the result of recession of the wall of grikes (Ford and Williams, 1989, p.391). 'Giant grikelands', 'corridor karst' or 'labyrinth karst' are assemblages of box valleys and platea and are documented to exist in tropical and temperate rainforests, in deserts, and in semi-arid areas and in the north of Canada (Ford and Williams, 1989, p.391; Gale *et al.*, 1997; Hamilton, 1995). "The prime requirements for such assemblages appear to be very major joint sets (often small faults with lateral displacements), massive strata, climatic or topographic conditions that permit a deep water table, and a long duration of sustained dissolution" (Ford and Williams, 1989, p.393).

From research of the karst topography in Sarawak, Wilford and Wall identified other factors responsible for cliff formation and recession including:

"(a) undercutting by solution at the foot of the cliffs combined with gravity collapse; (b) differential erosion of weaker strata along faults; (c) differential removal of weaker strata from above and below gently dipping to vertical limestone beds; (d) differential erosion of relatively weak strata, including well bedded impure limestone; and (e) differential erosion of weaker intrusive rocks in the limestone" (Wilford and Wall, 1965, p.69).

The Campbell Uplift has small labyrinth karst in the upper end (around sites 15, 16, 18, E, and G) of the North Side of the Middle of Campbell Lake area (Figure 4.20) as well as what seems to be the beginning of labyrinth karst in the Quarry area (Q-2 and Q-4). The

depth of the valleys is 4 to 10 metres and they are 2 to 5 metres wide and approximately 100 m long. The type example is drawn in Figure 4.21 and is accompanied by a cross-section detailing its dimensions.

Figure 4.20: Example of the labyrinth karst in the Campbell Uplift

Figure 4.21: Sketch and cross-section of typical labyrinth karst in the Campbell Uplift

4.3.3.2 Pinnacle Karst

Pinnacle karst has residual hills of rock that are usually quite tall (some in excess of 45 m in Sarawak (Wilford and Wall, 1965)), although some might be only 2 m wide and high. Pinnacle karst develops dominantly in dense rocks, rocks that have very massive bedding, and rock that has well spaced major joints (Ford and Williams, 1989, p.391). A "... high degree of purity, a low primary porosity, poorly defined bedding, and a well defined, widely spaced pattern [as well as] ... mechanical strength and structural control ..." (Wilford and Wall, 1965, p.69) are necessary for cliff formation in limestone and, although not required, facilitate pinnacle development. However, this type of karst might also develop on rock without these characteristics. For example, pinnacle karst in Spitzbergen is found in carbonate breccia (Lundberg, 1999, Pers. Comm.).

Pinnacle karst can develop in many environments, from tropical rain forests to semi-arid areas in northern Australia. Burial and exhumation phases may be part of their development, as in Yunnan, China (Chen *et al.*, 1986), or it may not, as in Mt. Kaijende, Papua New Guinea (Williams, 1971). Pinnacles are most often formed from above, by exhumation of subsurface forms when the base level drops. On the other hand, development of pinnacles can proceed by the lateral degradation of a doline karst (Sweeting, 1978, 203-4). According to Sweeting (1978), the landscape in the first stage is made up predominantly of dolines. The dolines then develop into U-shaped valleys in the second stage and, in the third stage these valleys widen even further to leave isolated peaks, pinnacle karst. Pinnacles are known to be completely removed by glacier scour (Ford and Williams, 1989, p.482) and, thus, are not as likely to be found in glaciated terrain as non-glaciated due to the time and

conditions required for this landform to completely develop.

Despite a semi-arid and glaciated environment in the Campbell Uplift, pinnacle karst appears to have developed. Pinnacles in this area are not large or sharp but are residual hills of rock about 50 to 65 metres high and 10 to 12 metres in width and breadth. They were observed in the North Side of the Middle of Campbell Lake, specifically site E (Figure 4.22). The base of the pinnacles is covered in a frost shattered debris talus. More developed forms are only 10 to 12 metres high and half this in width and breadth and are located on the steep valley side with considerable talus beneath (Figure 4.23).

Figure 4.22: Example of the early stage of pinnacle karst in the Campbell Uplift

Figure 4.23: Example of pinnacle karst (pointed outcrop in centre of photo) in cliff with talus slope

4.3.4 Karst Depressions

The karst depressions found in the Campbell Uplift are small scale features as opposed to, for example, poljes which can be several to many square kilometres. The genesis of the small karst depressions is attributed mainly to karst dissolution although it is recognised that in all likelihood periglacial processes have also played a role, perhaps in the preparation of the rock for dissolution or in the enlarging of the feature after it originally formed. Three solution dolines (a closed depression with underground drainage at least for some of the time) were observed in the Campbell Uplift. Two of these are specifically termed "stream sinks" as an actual channel leading underground was observed for each. Several rectangular collapse

dolines are also located in the study area.

4.3.4.1 Solution Dolines and Stream Sinks

Dolines are enclosed depressions in karst terrain. There are several different types of doline as described and explained by Cvijić (1893), Ford and Williams (1989, p.396-423), Jennings (1985, p.106-119), and Sweeting (1973, p.44-73). Their formation is directed by the permeability and porosity, usually secondary, of the host rock (Sweeting, 1973, p.50). Dolines are usually about 10 to 100 metres in diameter and 2 to 100 metres deep (Cvijić, 1893). There are four principal genetic classes of dolines: 1) solution; 2) collapse; 3) subsidence; and 4) suffosion (Ford and Williams, 1989, p.398) (Figure 4.2).

Figure 4.24: Four genetic classes of dolines from Ford and Williams, 1989, p.398, Figure 9.13.

Dolines can develop by dissolution of rock as water infiltrates joints and fissures. The joints and fissures are enlarged and the surface settles and lowers creating a depression. Solution continues and the 'normal' doline, usually circular or oval in shape, increases in size. A solution doline might lose surface support due to dissolution and form a collapse doline, although collapse dolines also develop completely isolated from any previous solution dolines. Collapse dolines involve the fracturing and rupture of rock and soil whereas subsidence dolines involve the gradual sagging of the surface without obvious breaks in the rock or soil. Subsidence is much less common than collapse dolines but, in fact, dolines often are of polygenetic origin. Suffosion dolines develop where there is "thick unconsolidated regolith or allochthonous detritus over karst" (Ford and Williams, 1989, p.412) rock. Suffosion is defined as the "evacuation of fines by a combination of solution and downwashing" (Ford and Williams, 1989, p.412) and can cause the surface of an area to be dimpled with small dolines. This type of doline tends to end in a subsidence type doline with the coalescence of more than one suffosion doline.

Stream sinks are closely related to dolines. Sinks are essentially the point in a depression into which surface water flows. The point at which this occurs is often, but not always, at (or close to) the base of a depression. It is also common at the termination of a blind valley. Water will flow into the sink and be removed from the area by an underground plumbing system. This system usually develops along joints, fissures, and faults which have been enlarged by dissolution. Water does not always flow in this underground system but if it does, the speed of draining depends on the capacity of the plumbing system. If there is insufficient water in the area of a sink then the sink will remain inactive until water is present.

'Disappearing' or 'intermittent' lakes are the result of substantial rainfall that accumulates in a depression but over time the water is evacuated by a sink and the lake water essentially disappears underground. The significance of a sink is that it indicates a subsurface drainage system although this system may only be seasonally active.

There are few obvious examples of dolines in the Campbell Uplift but two sinks were discovered. A lack of dolines in the study area is attributed to various factors based on karst research done in the Napier Range in Western Australia which also had few examples of dolines. (Goudie, *et al.*, 1990). These factors are:

- 1) available relief is modest and generally less than or equal to 150 m;
- 2) no observed cave systems for collapse to result from, which is also potentially a consequence of 1); and
- 3) sealing of valley floors by permafrost.

A solution proto-doline was located in the Road area. It is 2.2 m deep, 0.8 m wide, 2.1m long, and is shown in Figure 4.25.

Figure 4.25: Example of a solution doline in the Road field area

In the Campbell Uplift two stream sinks were identified in the Middle of Campbell Lake - North Side area, field sites D and F, in the large depression in this area. The sinks were actively funnelling water underground when discovered and it was obvious that there had previously been more water in the area as evidenced by sediment deposits on the surrounding vegetation. Although the region is semi-arid, it would appear that sufficient water accumulates in the depressions and is later discharged into the underground system by the sink-holes leaving behind a thin veneer of sediments due to slow draining of the water into the sink. The actual sink in both cases was only approximately 12 cm in diameter and they are shown in Figures 4.26 and 4.27.

Figure 4.26: Sink #1 (at end of pH metre probe) in the Campbell Uplift

Figure 4.27: Sink #2 in the Campbell Uplift

4.3.4.2 Collapse Dolines

Collapse dolines are the result of removal of the support at the base of a landform. The collapse material is then either removed by mass movement, fluvial processes or dissolution, or it remains in place. A possible reason for such features in the Campbell Uplift is dissolution along bedding planes, joints or fractures causing mechanical weakening, removal of support, and collapse. The absence of remnant collapse material is attributed to the processes of dissolution. The collapse features in the Campbell Uplift are bounded by joints or fractures in the rock which is not surprising as these are zones of weakness along which the rock broke away. Frequent evidence of lateral undercutting indicates a potential access

to an underground plumbing system of some sort.

Collapse dolines were documented in the Falcon Lake area, at sites 5 and 6, and at the Bottom of Campbell Lake, sites 2 and 9 (Figures 4.28 and 4.29). These sites are within close proximity to cliff or fault edges, which cause high hydraulic gradients. The type example of this feature is square, having sides which measure 2.8 m, has a depth of 0.9 m, and in one corner it is undercut. The undercutting into the ground is at a 35° angle and extends in at least 1.4 m (measured by probing with a wooden rule). At its mouth the undercut is the full depth of the depression but its height decreases steadily as it goes into the ground.

Figure 4.28: Example of rectangular collapse doline in the Campbell Uplift

Figure 4.29: Example of a rectangular collapse doline in the Campbell Uplift

4.3.4.3 Collapse Resurgence

This feature is a large collapse (Figure 4.30) with a remnant ogive feature. It is not a collapse doline but resembles a collapsed cliff face in which there previously was a cave (although no cave passage was discovered). The collapsed blocks are about 1 m² on average and have evidence of surface dissolution. There is surface karren on different sides of the blocks. The collapsed blocks presently cover a surface area of about 8 metres squared. Level with an etched bedding plane is the bottom of the ogive feature which is approximately 20 cm across at the widest point and 30 cm high. The ogive feature is angled into the hill side and there are large fracture surfaces on either side of the ogive. It is hypothesised that, due to the ogive feature, this was originally a cave entrance that has collapsed. There is box-work on the vertical surface of the fracture area to the left of the ogive feature.

Figure 4.30: Collapse resurgence with an ogive feature (not seen)

4.3.5 Precipitation Surfaces

Precipitation of calcite is common in karst environments and indirectly indicates that dissolution has occurred. It occurs when the water in solution is supersaturated with respect to the mineral it is dissolving; when the back reaction of the solution of a mineral predominates (Ford and Williams, 1989, p.50). The saturation index (SI) of a mineral measures the extent to which the sampled water deviates from equilibrium, or its "aggressivity". If a water is aggressive it will dissolve the mineral, for example dolomite, but when it becomes more saturated than its equilibrium state it is "non-aggressive" and may begin to precipitate its solutes. Precipitation does not always occur when the SI equals 0.00 due to the energy barrier that must be overcome prior to the start of deposition. In optimum karst environments precipitation may begin at $SI_{C \text{ or } D} = 0.30$ (for calcite, _C or dolomite, _D) (Ford and Williams, 1989, p.94). In general, calcite precipitation occurs quickest onto calcite already present due to the match in the chemical lattice of the precipitate and will readily occur onto carbonate rock surfaces.

Precipitation of carbonate usually occurs when running water comes in contact with rock and the outside atmosphere simultaneously. Solubility increases with an increase in P_{CO_2} . The P_{CO_2} is usually higher in soil and underground structures, such as vugs, fractures, and caves, than in the atmosphere. Therefore, it is necessary for the water to be in contact with the outside air so that it can release its CO_2 to the atmosphere. This decreases the solvent capacity of the water and effectively results in the precipitation of some of its solutes (Ford and Williams, 1989, p.50-4, 123).

Calcite is the principal precipitate (Ford and Williams, 1989, p.329) in karst

environments. In the Campbell Uplift calcite precipitation was found in all field areas on rock surfaces, including the undersides of pebbles, rock fragments, and freshly wedged or shattered rock surfaces and their parent rock. The precipitate is illustrated by two type examples. In the first, it resembles a thick coating of white to cream coloured paint or plaster on the fracture and joint surfaces of a cliff face. The precipitate is only 2 to 3 mm thick but covers the visible rock surfaces. In the second example the precipitate is relatively thick. It resembles small pieces of popcorn 4 to 6 mm large and is located on the underside of hollows and rock overhangs. Neither type was chemically analyzed but investigation of the surrounding rocks and application of acid to some of the precipitate indicated that the white coating on the rocks was most likely calcite or composed dominantly of calcite. In Figure 4.31 the calcite 'paint' or 'plaster' is visible on most of the rock surfaces and specifically on the third block to the left of the water bottle.

The presence of calcite precipitate on many different types of surfaces of rock in the Campbell Uplift indicates that saturated water has entered the joints and fracture areas and deposited the calcite in between the rock fragments. The calcite may have been deposited on open joint surfaces prior to frost wedging of the rock or afterwards on the exposed surfaces. Precipitation is often the end result of dissolution along the path the water has travelled. Since frost action occurs yearly and many newly frost shattered rocks have calcite precipitation on at least one surface, the precipitation is presently occurring in the Campbell Uplift environment. Samples of the precipitate were taken from the field to be dated at a future date.

Figure 4.31: Example of precipitation resembling calcite 'paint' or 'plaster'

Carbonate deposition can also occur due to evaporation which is common in arid and seasonally arid environments (Ford and Williams, 1989, p.123). The Campbell Uplift is classified as such an environment and some of the carbonate precipitation is likely due to evaporation. Cream coloured globular shapes, only millimetres in size, are typical examples of evaporitic deposits found at cave entrances and in seasonally dry caves (Ford and Williams, 1989, p.331). Thus, it is not surprising to find these popcorn shaped calcite features in the Campbell Uplift considering its arid climate.

4.4 PERIGLACIAL LANDFORMS

Periglacial landscapes result from the combination of the effect of the presence of permafrost and annual or short-term freezing and thawing. The terrain of the Campbell Uplift is affected by both these conditions. Freezing and thawing of water in rock depends on the available water within the ground, temperature fluctuations, and rock properties including lithology, pore size, permeability, and degree of microcracking.

The expression of the processes of frost shattering and frost wedging are prevalent throughout the study area, as are frost pockets. Solifluction surfaces are found in some areas of the Campbell Uplift. Other common periglacial landforms such as patterned ground, ice wedges, and pingos are not found within the Campbell Uplift because these are characteristic of terrain with sediments rather than rock outcrop. Since much periglacial research addresses features and processes of sediments there is not a lot of literature on periglacial features of rock outcrops.

4.4.1 Frost Action: Frost Shattering and Frost Wedging

"Cryogenic weathering refers to the combination of mechanical-chemical processes which cause the *in situ* breakdown of rock under cold-climate conditions" (French, 1996, p.40). Frost action, a form of cryogenic weathering, is a general term used to describe the processes resulting from freezing and thawing of rock, soil, and other materials. Frost action is a fundamental characteristic of periglacial environments and frost action tends to reach its greatest intensity in these areas (French, 1996, p.31&41). Mechanical weathering is the disintegration and breakdown of soil and rock material. It commonly occurs through frost

action which involves the freezing of water in pore spaces, joints, and bedding planes in rock. Two specific processes are: 1) frost heave which occurs as water changes state during the period of freezing, and 2) thaw weakening and settlement, which occurs during the thawing of seasonally frozen ground.

Frost action occurs when water present in rock or soil in periglacial environments freezes and eventually thaws. Rock under periglacial conditions is exposed to varying temperatures which cause water to freeze and expand. The water in rock will expand and subject the rock to increased pressures which will often be high enough to shatter the rock. Frost action occurs when there are frequent oscillations in temperature around the freezing point of water or when there are prolonged periods of freezing (Hallet, 1979). However, "...when this cracking takes place and what causes it are still not clear... microfracturing may not require freeze-thaw cycles or even falling temperatures but a constant sub-zero temperature. ... a high frequency of freeze-thaw cycles is not necessary for crack propagation, which can occur at temperatures anywhere between -4°C and -15°C " (French, 1996, p.41).

4.4.1.1 Frost Shattered Forms

Frost shattered rock fragments are generally angular and can range in size from several millimetres to several tens of centimetres depending on the lithology of the rock. The rock from which the fragments originated is left with an angular surface usually matching the fragments. Water can have greater access to certain rocks due to jointing, vugs, previous rock shattering, dissolution of the lining of vugs, joints, and other lithological weaknesses.

Weakened rocks are more likely to experience frost shattering than rocks that are not already weak. For example, rock that is dissected with many fractures will shatter more readily than a homogeneous, unfractured rock.

The frost shattered debris in the Campbell Uplift displays typical sharp edges and ranges in size from several centimetres, particularly where there are calcite patches in the rock, to tens of centimetres, characteristic of the talus slopes (Figure 4.32 and 4.33). Frost shattering was documented at 34 sites in the Campbell Uplift and the majority of the shattering was of Vunta formation rock (30 out of 47 sites).

The type example of the effects of frost shattering is found at a 4 metre high rock outcrop with the top surface covered in vegetation (moss, lichen, small bushes). The rock surface is nearly vertical, interspersed with thin and thick bedding, and there are many sharp edged rock fragments at its base. The rock fragments are divided into two average sizes: 5 cm long, 3 cm wide and thick and fragments that are twice or three times this size. They are shattered from the rock surface above as evidenced by the sharp edges from which rock fragments can be fitted back into their original place. The two different sizes of fragments relate to the different bedding; the larger pieces from the thicker bedding and the smaller rock fragments from the thinner bedding. More rock has been removed from the thin beds than the thicker, relatively more massive beds, although shattering has occurred from all surfaces. The vertical edge of the rock outcrop is more indented at the thinner beds than at the thicker bedding surface. This indicates that thinly bedded rock is typically more susceptible to frost action in the form of shattering in the Campbell Uplift.

Figure 4.32: Example of frost shattered pieces of rock at the base of a cliff

Figure 4.33: Example of frost shattered pieces of rock forming cliff talus

4.4.1.2 Frost Wedged Forms

Frost wedging is often, but not necessarily, of larger rock pieces than frost shattering. The rock is fragmented from the bedrock, along lines of weakness to which water has access, and is subsequently moved away from the parent rock in any direction. The weakened areas of the rock, similar to frost shattering, can be caused by dissolution of the lining of vugs, joints, etc., as well as previous frost action and lithological weaknesses.

Frost wedged debris was not found in as many field areas in the Campbell Uplift as examples of frost shattering. Examples of frost wedging were documented only in the Middle of Campbell Lake - North Side and the Quarry field areas, at a total of nine field sites. Frost

wedging is less common than frost shattering as it is only evident in 21% of the field sites compared with 61% of the field sites that have evidence of shattering.

There are two "type" examples of frost wedging in the Campbell Uplift. One is a surface of rock in which individual pieces of rock have been dislocated from their place of origin by approximately eight centimetres (example shown in Figure 4.34). The surface resembles a pavement and the sides of the pieces of rock are smooth. This indicates that the rock was prepared by dissolution which might have facilitated wedging. The actual pieces of rock are 30 cm long and wide and of unknown depth. The second type example is of much larger pieces of rock (shown in Figure 4.35). The rock pieces for this second type are

Figure 4.34: Example of small frost wedged blocks of shillow-free pavement

approximately 75 cm long, wide and high and are found in beds that are larger than the previous type. This type of frost wedged block does not show evidence of preparation by dissolution although dissolution seems to have occurred post-wedging as evidenced by surface karren that does not match between two blocks that originally would have been joined.

Figure 4.35: Example of large frost wedged bedrock

4.4.1.3 Frost Pockets

Frost pockets are superficially similar in appearance to the beginning of a solutional cavern in the side of a rock face. The difference is that instead of having a smooth dissolutional surface, the frost pocket generally has a jagged texture to its walls. In addition, a dissolution surface often is the characteristic dark grey colour of cyanobacterial coatings while the frost pocket surface is the colour of the fresh rock. The texture and colour of the frost pockets are due to the process creating the feature, frost action. This process requires the presence of water. Instigation of frost pocket formation is located where there is contact between water and rock, some sort of lithological weakness, excess vugs, more joints than elsewhere, or chemical incongruity with the rest of the rock face. Once an area of the rock face has responded to intense frost action and the rock has shattered, the process will continue and the frost pocket will continue to develop. Frost action often propagates from a starting point to produce semi-circular pockets that are no longer in contact with the water that initiated their formation. This occurs because the microfracturing caused by the frost action propagates into the rock beyond the immediate evidence of the shattered surface. This allows continued water penetration into the rock. Since water can accumulate in rock hollows, frost action focusses on these areas and creates an even larger hollow in which more water can accumulate. Thus, the positive feedback process continues to enhance the form of the pocket.

Frost pockets range in size from only a few tens of centimetres to several metres in diameter depending on the rock's size and ability to maintain the structure of a pocket without collapse. This periglacial landform was noted in 16 of 47 field sites in the Vunta Formation

rock (34%) and none were found in the Gossage Formation. Overall, frost pockets were only located in 28% of the field sites.

Figure 4.36: Example of a large frost pocket - 1.7m across at widest point

In the Campbell Uplift the type example of a frost pocket is 25 cm at the highest point, 35 cm at its widest, and 40 cm at its deepest point. The frost pocket has a thick layer of frost shattered debris (6-11 cm) on the near horizontal surface. The rock fragments are quite small and similar in dimension to the smaller size frost shattered debris from thinly bedded rock (section 4.4.1.1); 5 cm long, 3 cm wide and thick. The size of rock fragment in other examples of frost pockets depends on the size of the beds in which it formed. The more massive rock surfaces with frost pockets also had small rock fragments. Although this type

example is not too large, a few frost pockets in the Campbell Uplift were as large as 3 metres across and 1 metre high as shown in Figure 4.36.

4.4.2 Solifluction Lobes

Solifluction of the earth is the slow downslope movement of water-saturated soil (French, 1996, p.10). Various terms have been used to describe this type of landform process but 'solifluction' will be used here. Generally solifluction occurs when part of the active layer melts, from a few centimetres to two metres (Williams and Smith, 1989, p.125), and the meltwater saturates the soil but cannot penetrate the frozen ground beneath. This causes the soil to flow very slowly down gradient even if the slope is inclined only a few degrees (Williams and Smith, 1989, p.126; Bloom, 1998, p.176). The soil moves downslope in a "rolling motion like the endless tread of a tracked vehicle" (Bloom, 1998, p.176). The soil movement that occurs in solifluction is slow and annual displacements may be only several centimetres; average rates of movement are between 0.5 and 10.0 cm/year (French, 1996, p.152; Williams and Smith, 1989, p.126).

In the Campbell Uplift, solifluction surfaces generally were evident where there was more vegetation cover (grasses predominantly) and not a lot of rock outcrop. This is not unusual because this process needs loose material in which to work such as soil, peat, vegetation mats, or even shattered bedrock flakes. Solifluction lobes were recorded in 6 of 10 field sites in the Falcon Lake area and at 1 site (of 8) in the Middle of Campbell Lake - South Side. Generally, the lobes were very poorly formed because there was so little thickness of loose and rounded material on which they could properly develop. The shattered

bedrock found in some field areas was angular and, thus, not conducive to the development of solifluction lobes. Therefore, the paucity of examples in the upper field areas is not surprising due to the inadequacy of the surface material; much of the northeast field areas are dominated by rock surfaces or the rock is only thinly covered by vegetation.

Figure 4.37 shows the type example of solifluction lobes which is at the southern end of Falcon Lake area, field site 7. The slope angles of the lobes ranged from about 10 to 20° despite an overall slope as inclined as 35°. The surface material was relatively thick (estimated at 15-20 cm) and covered by vegetation, predominantly various types of moss and lichen. Between the solifluction lobes there are patches of rock which are unvegetated or thinly covered by vegetation.

Figure 4.37: Example of solifluction lobe (right side of hill) in Falcon Lake field area

4.5 GLACIAL LANDFORMS

The landscape of the Campbell Uplift was modified by glacier activity during the Wisconsin glacialiation. Depositional landforms such as moraines or drumlins were not observed in the field areas although a patchy, thin cover of glacial debris was observed on some surfaces in all six field areas. The glacial debris was a mixture of small pebbles, averaging up to 3 cm long, and fine rust coloured sand. The debris was consistent throughout the six field sites in terms of colour, texture, and distribution. Glacial erratics which are larger than the debris just described, were also observed in all six field areas. The generally fresh, unweathered nature of the surfaces of the erratics suggested that they are from the last (Wisconsin) glacialiation.

Glacial erosional landforms were a significant feature of the landscape. They were of four main types (discussed below) including plucked and scoured surfaces, glacial grooves, and whalebacks.

4.5.1 Glacially Plucked/Quarried Surfaces

Erosion by plucking (also called quarrying) is an important glacial processes. Plucking occurs due to rock failure along weaknesses, such as joints and fractures, and is the actual removal of a block of rock which is then carried away by the glacier. Plucking generally requires less work per unit volume than abrasion to wear down a similar rock (Small, 1976, p.376). It generally occurs on the downglacier side of slopes, the lee side, and creates many types of glacial landforms such as cirques, rock steps and basins, and the lee side of roches moutonnées (Small, 1976, p.376).

The process of plucking is thought to occur in one of two ways. As a glacier passes over an area its ice may freeze to the underlying rock. Since the glacier is moving the rock is extracted from the ground, breaking away along lines of weakness (such as joints and fractures). The second method of plucking is the sequence of water freezing and expanding in joints or lines of weakness in the rock and then this segment of rock is dragged away by the moving glacier above (Small, 1976, p.376-7; Chorley *et al.*, 1984). Freeze and thaw beneath a glacier is likely as the base of a glacier nears the pressure melting point (Hambrey, 1994, p.83).

The result of glacial plucking was noted only in three sites (sites 4, 5, and 6) in the Falcon Lake field area (example shown in Figure 4.38). These sites are in close proximity to the fault along Falcon Lake. Glacial plucking might prepare the surface for the development of karst pavements but it is impossible to differentiate between pavements due to glacial plucking and those due to abrasion without knowing what the terrain was like prior to glaciation. The horizontal surfaces left behind by plucking are not classified as pavements unless clints and grikes are obviously developed.

The type example of the effect of glacial plucking is the negative form of a box that would have been 1.9 m high and 8 m long and wide. The rock from which the blocks were plucked has a dip of 3° SE-NW. The surface left by the removal of the blocks is very flat and has limited vegetation (grasses, mosses, lichen, and evergreen trees). Glacial deposits approximately 2-5 cm thick are found on 65% of the horizontal surface. The vertical surfaces show jointing and fracturing that is currently being modified by frost processes and dissolution.

Figure 4.38: Example of the effects of glacial plucking in the Campbell Uplift

4.5.2 Glacially Abraded/Scoured Surfaces

The results of abrasion by glaciers are often dramatic (Hambrey, 1994, p.83). The erosive process of abrasion occurs by the sliding or moving of rock over other rock causing wear. Glacially abraded landforms include simple smoothed and polished surfaces (most common), striations, glacial grooves, and whaleback forms.

Abrasion occurs most often on the stoss side of a hill, the upglacier slope. It requires a wet-base glacier so that sliding of the glacier over rock surfaces is possible. Scouring is accomplished by the rock fragments within the glacial ice and not by the ice itself. These fragments will abrade the surface of the earth as well as other rock within the glacier. Glacial

striations and grooves can indicate the direction of flow of the glacier although local flow directions may cause complex patterns that make it difficult to determine the continuous flow of the glacial ice.

The effects of abrasion depend on the effectiveness (concentration, shape, and size) of the rocks scouring the surface, movement of the debris within the glacier and the glacier itself, the hardness of the rock being eroded and causing erosion, and the basal shear stress (weight) of the glacier (Bloom, 1998, p.373-381; Chorley *et al.*, 1984, p.446). Abrasion of rock by a glacier will occur until the basal load of the glacier becomes so large that deposition begins. Once enough rock has been deposited and the velocity of the glacier increases, erosion will start again (Bloom, 1998, p.375).

Glacially scoured surfaces in the Campbell Uplift were noted at 22 sites, 39%. It is presumed that the pavements and shillow covered pavements were most likely the result of glacial scouring and so these surfaces are classified as scoured.

The type example of the effects of glacial scour is a flat surface dipping 9° SE. The surface area is approximately 60 m long and 30 m wide. The majority of the surface is frost shattered although it is difficult to estimate how much because more than half of the surface is covered by vegetation thus hiding the expression of frost shatter. Two examples of glacial abrasion are shown in Figures 4.39 and 4.40.

Figure 4.39: Example of the effects of glacial scouring of thinly bedded rock

Figure 4.40: Example of the effects of glacial scouring in the Road field area

4.5.3 Glacial Grooves

Glacial grooves are the result of glacial erosion by scouring. Grooves can be carved out of soft sedimentary rocks as well as granites and gneisses (Hambrey, 1994, p.97). A groove is likely the enlargement of a glacial striation but can also have striations on their generally rounded surfaces (Hambrey, 1994, p.96-97). Stones or rock fragments caught in the base of a glacier erode bedrock surfaces by abrasion and can form thinly cut striations or larger grooves. Ice might get caught in the larger grooves and cause further erosion. The width and depth of a glacial groove can reach up to a few metres and the length can be several hundred metres although many grooves are much smaller (about a metre in width and depth)

(Hambrey, 1994, p.97; Bloom, 1998, p.375). As with generally scoured surfaces, glacial grooves can sometimes indicate direction of ice flow.

Glacial grooves were documented at 5 sites in the Falcon Lake area and 2 sites in the Bottom of Campbell Lake area. The grooves are generally only a few metres long and slightly less wide and deep, or they are very small. The type example of a glacial groove in the Campbell Uplift is 50 cm long and 20-30 cm wide and deep. It is parallel to the long axis of the whalebacks on which it is located and has not been modified by dissolution or frost action.

4.5.4 Whaleback

A "whaleback" is a smooth hillock of glacially eroded bedrock. This landform, appropriately named, resembles a whale in profile (Hambrey, 1994, p.280) or a small drumlin. They are generally several metres high, tens of metres in length and several metres in breadth. The sides of a whaleback may slope at angles of about 40 degrees (Chorley *et al.*, 1984, p.447). Whalebacks are similar in scale to roches moutonnées but are smooth on all sides whereas roches moutonnées have a plucked end.

Whalebacks are smaller but similar in form to rock drumlins. Rock drumlins are streamlined forms oriented parallel to the direction of ice flow. The long axis of a whaleback, like a drumlin, is parallel to the direction of ice movement. According to Hambrey (1994, p. 280) whalebacks are not common and clear examples of them are rare. A marked lack of documentation in the literature may reflect their scarcity.

Whalebacks are thought to be formed due to abrasion by moving glacial ice (Hambrey,

1994, p.84) whereas abrasion and plucking together form roches moutonnées (Hambrey, 1994, p.93). It is hypothesised that whalebacks "are likely to occur where the ice is thick, slowly moving and where bedrock structures favour small bumps" (Chorley *et al.*, 1984, p.447). Roches moutonnées are thought to "occur where the ice is thinner and fast-moving, and where bedrock structures form high amplitude bumps" (Chorley *et al.*, 1984, p.447). Thus, whalebacks will most likely form where the terrain has small bedrock hills and over which thick and slow moving ice has flowed. As exemplified by the Campbell Uplift, this is not always the case since it is unlikely that *thick* glacial ice reached as far to the northwest of Canada and the study area. The presence of whalebacks is, therefore, explained by the importance of topography. Since topography is very important in areas where the ice was thinner, whalebacks could have been formed as a result of large bedrock hills that were scoured by thin glacial ice. The long-axis direction of the whalebacks is predominately parallel to the jointing of the rock. This is reasonable since the thin glacial ice would have operated on these joints rather than acting parallel to the existing topography. Glacial grooves and striations are parallel to the long-axis of the whalebacks; evidence the glacial ice flowed generally east to west.

Whalebacks are predominantly found in the Bottom of Campbell Lake field area but they are also located in the Falcon Lake and Quarry areas. This feature is only found in 12% of the field areas. An unmodified whaleback has not been significantly altered by geomorphic processes including (but not exclusively) the periglacial processes of frost shattering and wedging, the karst process of dissolution, or any other weathering processes such as mass movement or geological faulting. Typically whalebacks lie parallel to other whalebacks and

in the Campbell Uplift their long-axis is perpendicular to the nearest fault. The type example has a smooth surface covered in small vegetation such as moss and lichen. It is typical of the Campbell Uplift whalebacks and has a width (at the base) of 10 m, a height of about 4 m, and a length of 25 m. The whaleback has gently sloping sides averaging 15° (the slope angle is approximated from a linear measurement since the slope is convex).

Some of the whalebacks in the Campbell Uplift have been modified by non-glacial processes since their formation during glacial times. These landforms are discussed in detail in Section 4.6.2 due to their complex formation.

4.6 COMPLEX LANDFORMS

Landforms do not always develop solely by one process. In an environment where more than one process occurs, either simultaneously or at different times, complex landforms may develop. In the Campbell Uplift undercutting and modified whalebacks are complex landforms that have developed due to the interaction of two or more of the following processes: karst, periglacial, and glacial.

4.6.1 Undercuts

Undercutting of rock faces is the result of lateral action at the base of a rock surface to form an indentation that might only be several tens of centimetres high but metres deep (horizontally). It can be the result of mechanical processes, specifically frost action in cold environments, or of dissolution. Frost action and dissolution both need water to occur. Available water is located mostly in the soil so frost action and dissolution occur at the soil-

rock interface. Frost action often propagates from a single susceptible starting point at the soil-rock interface to produce pockets that are semi-circular in form and no longer in contact with the soil. Dissolution, on the other hand, occurs wherever water is in contact with the rock so that it tends to dissolve laterally into the rock, not vertically, to form a slot-like feature. This often does not cause a loss of mechanical strength of the rock even for slots of some metres penetration depth, but many lead to mass movement if too much of the base of the rock is dissolved away or if the rock is mechanically incompetent.

The two processes, frost action and dissolution, may combine to cause undercutting of rock. Undercutting by dissolution can prepare a cliff surface for frost action and a frost pocket sometimes results. Therefore, it is often difficult to distinguish which process is responsible for undercutting, notably when the undercut is not extensively developed.

Cliff face undercutting usually extends several metres along the base of the cliff where the vegetation and cliff meet although it can also occur at the base of an isolated piece of bedrock. Dissolutional undercutting is usually observed at the base of a rock face where water has dissolved the foot of the rock but evidence of this process is also observed at a previous base level. The undercutting of rock by dissolution is often only tens of centimetres high but can cut several metres horizontally into the rock. Frost action undercutting is usually more balanced in terms of amount of rock removed laterally and horizontally. A combination of the two processes might produce large undercuts that are as laterally deep into the rock as high.

In the Campbell Uplift the undercutting observed was almost always at the vegetation and rock interface at the base of bedrock outcrops indicating that the undercutting was recent

as opposed to having occurred when a higher base level existed. The undercutting is often only several tens of centimetres high and deep although in a few places the rock was undercut more than a metre horizontally (Figure 4.41). Since it is very difficult to differentiate between undercutting due only to dissolution or frost action when the feature is quite small and since the undercutting in the Campbell Uplift is likely the result of both processes, the features classified as undercut in the study area are undifferentiated by process and classified as a complex landform.

Figure 4.41: Large undercutting on rock outcrop in the Campbell Uplift

Undercut rock was documented at 30 % of the total number of field sites. However, since undercutting is only documented in the Vunta Formation, it should be noted that it occurs in a slightly higher percentage (36%) of these sites. The type example is 30 cm high and 40 cm deep into the rock. It has a smooth surface with a few areas from which frost shattered rock might have been removed although no frost shattered fragments litter the ground directly beneath the undercut. "Lush" vegetation (moss, lichen) grows at the base of the rock and at some points along the base of the rock there is no vegetation, only wet soil indicating that water accumulates in the area.

4.6.2 Modified Whaleback Forms

In the Campbell Uplift whalebacks were formed originally by glacial processes but some of these landforms have since been modified by karst or periglacial activity. These features are classified as either slightly modified or as modified whalebacks. Both modified forms of the whaleback have similar dimensions to the glacial landform although they are sometimes slightly less wide and the slope angle of the modified whalebacks is greater than their original form. Dimensions for the type examples are given below.

4.6.2.1 Slightly Modified Whaleback

A slightly modified whaleback is one in which periglacial, karst or other weathering process has altered the whaleback such that the form is maintained but the surface has been altered. For example, if 1) the surface has been dissolved and a pavement has started to develop or is fully developed, if 2) karren is a dominant form on the slope of the whaleback,

or if 3) the surface of the whaleback has been frost shattered or wedged so that the glaciated surface is no longer entirely intact, then the effects of these, and other, processes would alone or together define a slightly modified whaleback.

In the Campbell Uplift slightly modified whalebacks are located in 7 sites only within the Vunta Formation. The type example of this landform is 6.2 m wide at its base, 3.2 m at its highest point, and 30 m long. At one end the whaleback tapers gently at an angle of 10° but at the other end is steeper having an angle of 80° . The sides of the whaleback are linearly measured at 35° and 47° on either side. The surface of the whaleback has been modified by glacial grooves, structural karren, and cockling, and has a few poorly developed clints and grikes (approximately 12 clints each having a surface area of 225 cm^2). 75% of the whaleback is covered by a thin layer of vegetation (moss and lichen).

4.6.2.2 V-shaped and U-shaped Valleys - Modified Whalebacks

The original glacially formed whaleback may be modified so that the smooth rounded sides of the whaleback are no longer a characteristic of the landform. The general shape of a small drumlinoid is still evident although it is not necessarily dominant. Well-modified whalebacks are best described by the resulting valley between two of these landforms. There are two dominant types of valleys, the V-shaped and U-shaped valley. The valleys are the result of different processes acting on the whalebacks but are also determined by the existing lithology. There are some modified whalebacks that do not fit in either category well and, therefore, are classified simply as 'modified' whalebacks.

4.6.2.3 V-shaped Valleys

The V-shaped valley is predominantly the result of extensive periglacial activity. The lithology is generally very susceptible to periglacial weathering such as frost shattering and frost wedging. The periglacial processes create a talus of frost shattered or wedged material that, in time, fills the valley so that it looks like a “V” instead of the original concave rounded shape between the glacially formed whalebacks.

V-shaped valleys are only found in two locations; the Middle of Campbell Lake - South Side, site 11 (type example), and North Side, site G. The type example of this feature has a slope of 40° on one side and 12° on the other. The less inclined slope is 20 m long whereas the steeper slope is only 3.2 m. The valley is vegetated but the vegetation is covering talus debris.

4.6.2.4 U-shaped Valleys

The U-shaped valley maintains the shape of the original valley that formed between the whalebacks although the new valley is wider. The sides of the whaleback have been weathered by geomorphic processes, such as dissolution, frost shattering and wedging or mass movement, and the valley has been widened. This is similar to the formation of the V-shaped valley. The difference is that the material removed from the sides of the whalebacks does not accumulate to form a talus but is transported away from the valley floor. In the absence of any evidence of fluvial action the material is presumed to have dissolved. This process allows the sides of the whaleback to be maintained at the original or even more vertical angle forming a U-shaped valley between whalebacks. The permafrost in the area

may induce any moving water to flow laterally, as well as downslope, increasing the likelihood of dissolution at the base of the whaleback sides. This would increase the potential for mass movement of any kind due to a lack of support from the base of the whaleback side. New material would be added to the valley due to these processes and then removed by dissolution to maintain a U-shaped valley.

U-shaped valleys are more predominant than V-shaped valleys and are found in 5 sites in 3 field areas. The type example, is asymmetrical, having an angle of 15° over 10.4 m on one side and an angle of 58° over 1.3 m on the other side of the valley. The valley is 3.4 m wide with a slope of 6° . The U-shaped valley is characterised by surface dissolution including cockling and some frost shattered debris. There are glacial deposits on the old whaleback surface. The line transect which records this feature includes smaller and larger U-shaped valleys and is dominated by massive rock.

4.6.2.5 Modified Whalebacks

This landform develops similarly to the V- and U-shaped valleys but has not reached a stage where one of the two valleys is dominant. Therefore, it does not belong to either of the two previous categories. There are four field sites with landforms belonging to this category and they are all located in the Falcon Lake field area. The type example of this landform is asymmetrical with one 2.8 m high vertical side and the other being inclined 33° and 3.3 m long. There are structural karren and frost shattering on the valley sides. The near-horizontal valley floor is wet, 6.8 m wide, and there is a bit of undercutting of the vertical wall. Figure 4.42 shows valley forms for modified whalebacks.

Figure 4.42: A theoretical sketch of a whaleback, a V-shaped valley and a U-shaped valley with a cross-section of the valleys

4.7 LANDFORM, LOCATION, AND LITHOLOGY

Field sites within each field area each have an associated lithology. Table 4.4 delineates the landforms and the lithologies for each field site in the Campbell Uplift. The field site numbers in Table 4.4 correspond to the numbers on the air photographs of each field area, Figures 4.43-4.48. The relations of landform and lithological characteristics are determined from the data presented in this chapter and are described and discussed in Chapter 5, Analysis.

N.B. Scale for Figures 4.43-4.48 is 1:20 000.

Table 4.4: The landforms and lithologies for each field site in the Campbell Uplift

Field Area		Falcon Lake Area										Bottom of Campbell Lake										
Landform / Sites	1	2	3	4	5	6	7	8	10	11	1	2	3	5	6	7	8	9	10	11		
Microkarren, Ppt.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
Splitkarren		x	x	x	x	x	x	x		x		x	x		x	x	x					
Grikes				(x)	(x)	(x)	(x)	(x)		(x)		(x)	x			(x)	(x)					
Shallow-free Pvt				x	x	x	x	x		x		x	x			x	x					
Shallow Pavement											x											
Bogaz																						
Labyrinth Karst																						
Pinnacle Karst																						
Dolines&Sink-holes																						
Collapse Dolines					x	x						x						x				
Frost Shatter Forms		x	x	x	x	x	x			x	x	x	x	x	x				x			
Frost Wedge Forms																						
Frost Pockets	x	x	x	x	x	x	x		x	x			x		x				x			
Solifluction Lobes				x	x		x	x	x													
Quarried				x	x	x																
Scoured							x	x		x		x	x			x	x					
Grooves		x	x		x	x				x					x				x			
Whaleback (W/b)		x										x				x	x	x				
Undercutting		x	x	x	x	x				x			x		x		x		x			
Slightly Mod. W/b		x	x					x		x												
V-Shaped Valley																						
U-Shaped Valley				x	x	x													x			
Modified W/b	x	x	x																			
Lithology Group	BG	DBG	DBG	B	B	B	A	B	B	B	GI	G	F	E	E	F	F	D	B	B		

Table 4.4 continued

Field Area	M of C Lake - South Side												Middle of Campbell Lake - North Side (Sites 1-21)															
Landform / Sites	5	6	7	8	9	10	11	12	1	3	4	13	14	15	16	18	19	20	21	A	B	C	D	E	F	G	H	
Microkarren, Ppt.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Splitkarren		x	x											x	x									x				
Grikes	(x)	(x)	(x)	(x)					x															x				
Shallow-free Pvt		x	x	x					x																			
Shallow Pavement		x	x	x										x						x								
Bogaz																												
Labyrinth Karst														x	x	x								x				
Pinnacle Karst																								x				
Dolines&Sink-holes																							x		x			
Collapse Dolines													x															
Frost Shatter Forms		x	x	x	x	x	x	x			x	x		x	x	x	x	x			x	x		x	x	x	x	
Frost Wedge Forms										x	x		x				x					x						
Frost Pockets					x	x	x				x																	
Solifluction Lobes		x																										
Quarried																												
Scoured		x	x	x					x					x					x	x				x				
Grooves																												
Whaleback (W/b)																												
Undercutting					x										x		x	x						x			x	
Slightly Mod. W/b			x	x																	x							
V-Shaped Valley								x																	x			
U-Shaped Valley															x													
Modified W/b																												
Lithology Group	M	M	E	E	E	FG	FG	L	FM	L	L	O	L	K	CK	KO	L	G	N	K	I	I,J	J	G/K	N	K	G	

Table 4.4 continued

Field Area	The Quarry and The Road Areas										
Landform / Sites	Q1	Q2	Q3	Q4	Q5	A1	A2	A3	A4	R1	
Microkarren, Ppt.	x	x	x	x	x	x	x	x	x	x	
Splitkarren	x									x	
Grikes		(x)		(x)	(x)						
Shallow-free Pvt		x		x	x						
Shallow Pavement		x		x	x					x	
Bogaz											
Labyrinth Karst		x		x							
Pinnacle Karst											
Dolines&Sink-holes										x	
Collapse Dolines											
Frost Shatter Forms	x	x	x			x	x	x		x	
Frost Wedge Forms	x	x	x	x	x	x	x	x	x	x	
Frost Pockets											
Solifluction Lobes											
Quarried											
Scoured		x	x	x	x	x			x	x	
Grooves											
Whaleback (W/b)		x		x							
Undercutting											
Slightly Mod. W/b											
V-Shaped Valley											
U-Shaped Valley											
Modified W/b											
Lithology Group	M	N	M	N	N	N	-	G,I	N	O

Figure 4.43: Falcon Lake field area with 10 field sites

Figure 4.44: Bottom of Campbell Lake field area with 10 field sites

Figure 4.45: The Middle of Campbell Lake - South Side field area with 8 field sites

Figure 4.46: The Middle of Campbell Lake - North Side with 19 field sites and 4 field sites from the Quarry field area (A1-A4)

Figure 4.47: The Quarry field area with 5 field sites

Figure 4.48: The Road field area, the whole area is 1 field site

CHAPTER 5: ANALYSIS

5.1 INTRODUCTION

The relation between lithological characteristics and landforms is examined in this chapter. The analysis addresses the question of whether a landform's *existence* is related to a specific lithology and, thus, a specific lithological characteristic. Analysis of the data for some landforms did not present any obvious relationships and a second question was posed which addressed whether certain landform *characteristics* (form and dimensions) vary with lithology. The results might then be the basis for a predictive model where a certain lithology could be expected to produce a certain landform or certain landform characteristics in such an environment. However, the relationships determined from the data (presented below) are not necessarily causal relations but simply associations determined from numbers; thus some can be expected to be random and have no geomorphological significance. Analysis of the relationships using geomorphological knowledge and field experience has helped to determine the logical and significant relations from those that are random and of no value for prediction of landforms based on lithological evidence. This is discussed in Chapter 6.

This chapter presents a discussion of the landforms identified in the Campbell Uplift and the controlling lithological characteristic(s) where identified from the analysis of the collected data. The landforms are reviewed in terms of the four landform categories defined by process, i.e.: karst, periglacial, glacial, and complex.

5.2 LITHOLOGY

A rock type was identified for each field site and landform. A summary of the information gathered from the microscopic lithology (carbonate rock type, insoluble content, homogeneity, and grain size) of the rock samples from the Campbell Uplift, all study areas combined, is presented in Table 5.1. The published geological map divides the carbonates only into the two formations: the Vunta (70% of the study area, mainly to the south and west) and the Gossage (30% of the field area, mainly to the north and east) based on geological time rather than on lithological properties. Table 5.1 is divided according to lithologies rather than time units; thus one lithology may be represented in both formations.

Table 5.1: A summary of the small-scale lithological properties of the 70 samples taken from the study area of the Campbell Uplift; the percent representation indicates the frequency of each class

Property	Class	Percent Representation
Carbonate rock type	Limestone	34%
	Iron-free dolomite	45%
	Ferroan dolomite	21%
Insoluble Content	<10%	35%
	10-20%	53%
	>20%	12%
Homogeneity	Inhomogeneous	61%
	Homogeneous	39%
Grain Size	Coarse	29%
	Medium	21%
	Fine	30%
	Very fine	20%

In the Campbell Uplift there are three types of carbonate rock: limestone, iron-free dolomite, and ferroan dolomite. For each of these rock types the general characteristics are presented in Table 5.2.

Table 5.2: A Summary of the lithological properties for the three carbonate rock types in the Campbell Uplift based on the 70 samples taken from the study area

Lithological Characteristic	Limestone	Iron-Free Dolomite	Ferroan Dolomite
Insoluble Content	0 - >20%	< 10%	0 - >20%
Homogeneity	Both	Inhomogeneous	Homogeneous
Grain Size	Fine and Very Fine	Fine	Coarse and medium
Rock Categories	C K L M N O	A B E F	D G I J

5.3 KARST LANDFORMS AND LITHOLOGICAL CHARACTERISTICS

The karst landforms described in Chapter 4 are individually discussed in relation to lithology. 33% of the distinctive landforms documented in the Campbell Uplift are karst forms. These are found predominantly in either iron-free dolomite or limestone. The rock is predominantly inhomogeneous and has an insoluble content of less than 20%. Karst landforms form equally in rocks of all grain sizes. The characteristics of the lithologies associated with karst landforms do not differ greatly from those of the Campbell Uplift in general (see Table 5.1); however, specific karst landforms require specific lithological characteristics to develop. These characteristics are detailed below in relation to each karst landform.

5.3.1 Surface Dissolution - Karren

Three main types of surface dissolution are identified in the Campbell Uplift and the influence of lithology on these forms is discussed below.

5.3.1.1 Microkarren and Cockling

Microkarren and cockling were observed in all the field sites. This suggests that there was no lithological characteristic that prevented their development and that varying lithological characteristics, either macro- or microscale, had no effect on where they developed or even if they developed at all. This is reasonable because in the presence of any soluble rock, dolomite or limestone, water and carbon dioxide will most likely dissolve the surface of the rock provided enough time is available for this process to occur. However, since freshly shattered pieces of rock showed signs of dissolution, it is reasonable to make the assumption that the amount of time required in the Campbell Uplift for dissolution to become visually apparent is less than a year. Extensive dissolution necessary for more spectacular karst landforms, such as grikes or caves, would require many thousands of years. Reduced time within a year during which karst processes may operate is one of the constraints placed on the development of dissolutional landforms in this arid and cold environment. However, features such as microkarren and cockling which are less demanding in terms of required amount of dissolution needed for formation can develop readily despite the reduction in available time. Therefore, in the Campbell Uplift development of microkarren and cockling is not affected by varying lithological characteristics, although they do require soluble rock on which they can develop.

The rock on which microkarren and cockling are found controls the shape of the features. Grain size, lineations in the rock, and presence of vugs or more soluble material contribute to the form of the microkarren and the cockling. Coarse grained rock tends to have larger dissolutional indentations than fine grained rock but the indentations are spaced further apart. Where there are lineations in the rock fabric the surface dissolution is elongated. It appears that the small indentations join in some locations to form larger microkarren. Vugs and the presence of soluble material, usually calcite, also dictate the shape of the surface dissolution. Vuggy rock has areas that are more easily dissolved than the rest of the rock, thus dissolution tends to concentrate in those areas and creates larger forms that are relatively widely spaced. Where the more soluble material is crystalline calcite (relatively rare) the dissolution of the rock generates indentations that have straighter edges than usual due to the rhombohedral crystal structure of calcite.

Since cockling was observed throughout the study area the mechanism of formation is likely to be detachment of flow at lithological inhomogeneities. On steep slopes the form is round; on less steep slopes the form is more oval where water remains attached for slightly longer. Although different rock properties may not dictate the presence of microkarren and cockling they do contribute to their form.

5.3.1.2 Linear-form Karren - Splitkarren

Splitkarren were observed in 35% of the field sites, predominantly in the Vunta formation, (groups A, B, C, D, E, F, G, K, M, and O). The properties of the rock on which splitkarren forms do not vary greatly from the characteristics of the lithology that are typical

of the Campbell Uplift and for karst features in general. 70% of these rocks are dolomite and 30% limestone, most of these rocks (83%) have an insoluble content of less than 20% and most samples are medium to coarse grained (15 of 23).

Rock types I, J, L, and N are not represented in the samples of rock from the splitkarren field sites. There are no apparent factors that are similar between these four rock groups; I and J are dolomite, L and N are limestone. They have different amount and size of impurities, grain size, and insoluble contents. The only common rock factor found in splitkarren field areas that is evident is that the splitkarren develop primarily in the Vunta formation and there are few examples in the Gossage formation. Evidently, much of the Vunta formation has minor joints, veins, or micro-fractures since splitkarren are prevalent throughout the area.

5.3.1.3 Linear-form Karren - Grikes

The smaller grikes were located on the pavements while the larger grikes were located in only three sites. The first population is found primarily in the southwestern field areas, part of the Vunta Formation, but there are also some examples in the Gossage Formation. Their development is due to the presence of the pavements which will be discussed in the next section (5.3.2). The larger grikes are located in the Vunta Formation in the Bottom of Campbell Lake and the Middle of Campbell Lake - North Side field areas.

The existence of two populations of grikes indicates that they were formed at different periods in history. The large grikes identified in this study most probably required a long time to develop. Since there are only three examples of the larger grikes while the majority of

grikes are much smaller, it is presumed that the two populations of grikes formed at different times, the larger grikes prior to glaciation and the smaller grikes since. The larger grikes might not have been completely destroyed by glacial processes, with only the top of the grike being removed; dissolution processes after glaciation continued to enlarge the existing form of the grike. Presently this population of grikes is large due primarily to the fact that they already had a form at the end of glaciation; thus the difference in size is probably not related to lithological differences.

5.3.2 Pavements

Pavements, both shillow free and shillow covered, are widespread in the Campbell Uplift. They are most often noted in the Quarry and Road field areas which are part of the Gossage formation. Since pavements often develop in areas scoured during glaciation it is reasonable that they are prevalent in the study area. Pavements are generally found on iron-free dolomite with a low insoluble content ($< 10\%$). All grain sizes are found in pavement rock but fine grained rocks are most common followed by medium grained. Pavements are found on bedding that is horizontal or only slightly dipped ($< 10^\circ$).

Pavements without shillow are located in all field areas in the Campbell Uplift but they are less predominant in the Middle of Campbell Lake - North Side than in the other field areas. Shillow is not found in Falcon Lake or the Bottom of Campbell Lake field areas. Both types of pavement are present on both the Vunta and Gossage Formation. Within each field area the proportion of shillow-free pavement to shillow varies. Table 5.3 presents details about the field sites at which the existence of pavement was identified. For each field site the

number of pavement examples is compared to the total number of karst landforms documented for each field site and is expressed as a percentage. For example, in the Falcon Lake field area 22 examples of karst landforms were identified and, of these, 6 were pavement (either shillow or shillow free). Therefore, the percent of karst landforms that are pavements for the Falcon Lake field area is 27%. Also for each field area, the amount of shillow-free pavement is expressed as a percent of the total number of field sites with either type of pavement. For example, in the Bottom of Campbell Lake field area, of the total number of field sites with pavement features, 80% are shillow free and only 20% have shillow cover.

Table 5.3: The proportion of pavement examples to karst landforms and the proportion of shillow-free pavement to shillow pavement in each field area

Field Area	% of karst landforms that are pavements	Shillow-free Pavement - % of field sites
Falcon Lake	27%	100%
Bottom of Campbell Lake	31%	80%
Mid. of C.Lake-South Side	55%	50%
Mid. of C.Lake-North Side	18%	33%
Quarry and Road	47%	43%

In relation to the karst landforms documented, pavements are most prevalent in the Middle of Campbell Lake - South Side field area. Shillow-free pavements are located in a higher percentage of the field sites in the Falcon Lake area than elsewhere. There is a trend in the percentage of shillow-free pavements to shillow within each field site: the further northeast the site the greater the proportion of shillow.

All pavements emerge from glaciation similarly smoothed and all are subject to the same processes of dissolution and frost action, but some develop into clint-and-grike pavement while other disintegrate into shillow; the lithology might be expected to control the mode of development. Table 5.4 documents the lithologies associated with the different pavement types. In the Campbell Uplift the iron-free dolomite is presumably more mechanically competent than the limestone on which shillow forms. The pavements without shillow are typical of other pavements cited in the literature as they form on relatively pure dolomite and limestone (insoluble content less than or equal to 12%). The bedding characteristics of pavements in the Campbell Uplift coincides with the pavements in Dodo, NWT, where the shillow-free pavements were predominantly located on more massive units and the shillow covered pavements were on the ripple bedded units (Lundberg and Ford, 1994). The lithological characteristic of bedding is an important filter for the development of specific pavement type, either shillow-free or with shillow.

Table 5.4: Lithological characteristics for pavements in the Campbell Uplift

Pavement Type	Lithology	Rock Type	Insolubility	Grain Size	Bedding
Shillow-free pavement	A B E F G M N	Fe-free dolomite	Low	Medium - coarse	Thick
Shillow pavement	E I K M N O	Limestone	High	Fine - very fine	Thin

5.3.3 Large Karst Features Related to Grikes and Pavements

5.3.3.1 Bogaz, Giant Grikelands, Corridor and Labyrinth Karst

The corridor karst in the Campbell Uplift is formed mainly on inhomogeneous fine to very fine grained limestone with a medium to high insoluble content (9%-27%, average 15%). The corridors are parallel to the faulting and to the major joints in the area, therefore they intersect, but not always at right angles. The form of the corridors is maintained by means of mass movement due to frost action and by dissolution of that material. The requirements set out by Brook and Ford in 1978 for labyrinth karst are based on their research in Nahanni, NWT. The requirements are low porosity and primary permeability, massive carbonates, and widely spaced fractures (joints or faults) that are vertically and horizontally extensive. Low porosity and primary permeability could be verified in future studies of the Campbell Uplift but massive carbonate was noted in this study in the field areas with labyrinth karst. Joints and faults are prominent in the relevant field areas.

The requirements set out by Ford and Williams (1989, p.393) for this landform, based on their field work and that of others, are major joint sets and massive strata together with a deep water table and long duration of sustained dissolution. Although the authors do not specify precisely how deep the water table must be nor the exact duration of the dissolution, these requirements are discussed in terms of the Campbell Uplift for lack of other criteria with which to compare the requirements for development of labyrinth karst. The first two components are characteristic of the northern part of the Middle of Campbell Lake - North Side field area but the last two are not. Despite the lack of a deep water table and long dissolution, the labyrinth exists. This is compared with the labyrinth karst of the Dodo area

in the Northwest Territories where labyrinth karst also exists in a permafrost zone. The Dodo labyrinth karst is attributed to karstification that occurred prior to and since the Wisconsinan glaciation (Hamilton, 1995). Glacial action is thought to have enlarged the features, specifically the corridors, that developed during permafrost conditions prior to glaciation, as well as infilled some of the fissures with glacial debris. The Dodo labyrinth karst developed in massive strata as did the labyrinth karst in the Campbell Uplift. Based on the above reasoning, microscopic lithological controls are not as important as geologic structure (faulting, jointing, bedding).

5.3.3.2 Pinnacle Karst

Pinnacle karst is evident in one field site. The rock type of this field site is categorized as type G and K, ferroan dolomite and dolomitic limestone. These two rock types are quite different, G has vugs, is homogeneous, and has an insoluble content of 10.5% whereas K is smooth, inhomogeneous, and has a 20% insoluble content. One similarity of rock type K and G is the fine grain size. The field site has thin and thick bedding, as opposed to massively bedded rock. The field site is close to the border between the Vunta and the Gossge formations and is part of the Gossage formation, the younger of the two.

The lithological features of the rocks do not conform with the characteristics that facilitate pinnacle development as described by Wilford and Wall (1965) (Sect. 4.3.3.2). It is hypothesised, based on the evidence of the Dodo karst (Hamilton, 1995), the arctic karst in Spitzbergen (Lundberg, 1999, pers.comm.), and the Campbell Uplift karst that pinnacle karst may develop in two different types of environment with specific sets of characteristics.

The first set of conditions is that described by Wilford and Wall (1965) and by Ford and Williams (1989, p.393): massive rock, deep water table, long dissolution time, and major jointing, in an environment where lateral and vertical dissolution and lowering of base level produces sharp pinnacles. The best example of this is the stone forest in China (Sweeting, 1978). The other set of conditions is that present in various arctic environments: massive bedding, cliffs or fault edges, where frost action and karst dissolution combine to back cut into the cliff face so that remnant pinnacles evolve. These pinnacles are not as sharp as those described first (i.e. China's stone forest) and are only about 10 metres high. The base of the cliffs on which the pinnacles develop is talus. Therefore, despite most examples of pinnacles being from seasonally humid tropics, the second method of their development, the combination of frost action and karst dissolution on cliffs of massive rock, seems reasonable to explain the presence of such forms in the Campbell Uplift. These forms are caused by the combination of processes in a particular topography.

5.3.4 Karst Depressions

5.3.4.1 Solution Dolines and Stream Sinks

There are two stream sinks and one example of a solution doline in the Campbell Uplift. The doline is formed in rock of type O which is very smooth, very fine grained limestone, with a medium-low insoluble content of 11%. One stream sink is in rock of type J and the other is of type N. Rock type J is fine grained, ferroan dolomite with a high insoluble content of 24%. Rock type N is dissimilar as it is very fine grained limestone with a 9% insoluble content.

The two stream sinks were located in the two large depressions in the Middle of Campbell Lake - North Side field area. The dissimilar rock types indicate that the location of the stream sinks is more related to topographic position than to smaller-scale rock properties such as grain size and even insolubility. Jointing is usually very significant in defining stream-sinks but due to vegetation cover it was impossible to see jointing near the sinks. No other sites with a similar topographical situation to that of the sites with dolines were identified during this field work.

Stream sinks were noted in two places in the Campbell Uplift. They were discovered only because of the running water and would otherwise have been obscured by vegetation. Other stream sinks may exist in the study areas but were undiscovered because there was no water draining into them during field investigations. The existence of two sink-holes indicates that there is a subsurface drainage system and that there may be other points of access to this system, most likely through other sinks or joints. These points would best be found during spring melt or directly after a rainstorm.

5.3.4.2 Collapse Dolines

Collapse dolines are located in four field sites, predominantly in dolomitic rock, and only in the Vunta Formation. Insoluble content of the rocks is medium, between 10 and 20%, but other lithological characteristics are not similar among the rock categories which are represented in the collapse landforms. Geologic structure, including joints and fractures, are most likely an important control on this feature in the Campbell Uplift. Dissolution of the collapse material after collapse is important and is not specifically dependent on rock

characteristics other than that the rock is dolomitic and has a medium insoluble content. The collapse dolines in the Campbell Uplift are all located in close proximity to cliff or fault edges. This indicates that there is the possibility of dissolution at depth which would allow undercutting of the bedrock so that large chunks of rock could collapse. If the hydraulic gradient is low, for example far from a cliff edge, then the potential for dissolution is decreased. Therefore, the collapse dolines in the Campbell Uplift are located in areas that are reasonable, and likely, for their existence.

5.3.5 Precipitate Surfaces

Precipitation of calcite is noted in all field sites in the Campbell Uplift. There is no specific rock characteristic to which the precipitate is limited. The amount of precipitate is likely related not to lithology as much as to micro-climatic variables such as amount and frequency of precipitation, snowmelt, evaporation, and wind exposure. The type example of the popcorn precipitate was found in site 10 of the Falcon Lake field area and is from the rock type B. This rock type is coarse grained, iron-free dolomite with an insoluble content of 11%. There is no reason for increased dissolution of this rock compared to other rocks in the field area, therefore the large thickness of the precipitate generating the popcorn effect is most likely due to climatic or non-lithological factors.

5.4 PERIGLACIAL LANDFORMS AND LITHOLOGICAL CHARACTERISTICS

The periglacial landforms are not as diverse as the karst landforms but they comprise 33.7% of all the documented forms in the Campbell Uplift. The field areas with the highest

percentage of periglacial landforms are the Quarry and Road areas where 45% of the landforms are periglacial. Most periglacial landforms are found in rock that has a medium insoluble content between 10 and 20% and is fine or very fine grained. Unlike karst landforms, periglacial features are found predominantly in dolomite rock but are not specific to homogeneous or inhomogeneous rock, although vuginess is relatively important. The bedding characteristic of periglacial landforms varies according to the landform and is discussed below.

5.4.1 Frost Action: Frost Shattering and Frost Wedging

5.4.1.1 Frost Shattered Forms

The result of frost shattering is evident in all rock categories except for type D. This type of rock is medium grained ferroan dolomite and has an 9% insoluble content. It is dominantly massively bedded, making it less susceptible to frost shattering than the other rock types. Otherwise it is not remarkably different from the other types. In general the field sites where the effect of frost shattering was not observed are predominantly massively bedded or the bedding of the rock was not easily discerned. This coincides with the fact that in the Campbell Uplift massively bedded rock had less frost shattered debris than thickly bedded rock which, in turn, had less frost shattered debris than thinly bedded rock.

Examination of the lithological properties most often recorded for areas with frost shattering include medium insolubility (10-20%) and fine grained (but not very fine grained) rocks. Iron-free dolomite, ferroan dolomite, and limestone were similarly represented in the samples. Thus, frost shattering appears to be controlled mainly by thickness of bedding, the

thinnest-bedded rocks being the most susceptible. Since water is likely to penetrate the bedding planes, thinly bedded rock would have greater surface area for frost shattering to occur thus making it more susceptible to the effects of frost shattering than thickly bedded rock.

5.4.1.2 Frost Wedged Forms

The result of frost wedging was documented in eight rock types (F, G, I, J, L, M, N, and O). 63% of rock of sites with frost wedging were limestone. More than half the sites had an insoluble content for the rock of less than 10% and were relatively homogeneous. 95% of the frost wedged rocks are fine or very fine grained. The characteristics of the rock affected by frost wedging are different than those rocks affected by frost shattering, indicating that lithology is a filter in the development of these periglacial features due to different types of frost action. Fine grained and pure limestone is affected by frost wedging whereas frost shattering occurs regardless of the microscopic rock characteristics in the Campbell Uplift. Frost wedging is more prominent in areas with thick bedding over massively bedded rock. Thin bedded rock was not common in areas with frost wedging.

5.4.1.3 Frost Pockets

Frost pockets in the Campbell Uplift were only recorded in the Vunta Formation and six rock types were documented for this feature (A, B, E, F, G, L). Frost pockets form predominantly in iron-free dolomite with medium insolubility (10 - 20%) and a tendency to large grain size. The rock is not specifically inhomogeneous or homogeneous. The rock in

which frost pockets form is surprisingly dissimilar to the rock affected by frost shattering. This is surprising because the frost pocket is formed, in part, by frost shattering. Therefore, it is most likely the long-term presence of water with little evaporation and rock susceptibility to microfracturing that will permit continued frost action and, thus, control where frost pockets develop. The occurrence of frost pockets was noted most frequently on massively bedded rocks. This is reasonable since bedded rock tends to shatter into elongated forms parallel to the bedding whereas massively bedded rock can form more circular formations, such as frost pockets. Frost pockets in non-periglacial areas such as the Niagara Escarpment are associated with sites of emergence of groundwater, i.e., with bedding and with jointing. Here in the Campbell Uplift groundwater does not flow freely from beds and joints; instead the frost pockets are positioned where the seasonally melting active layer provides a source of water.

5.4.2 Solifluction Lobes

The solifluction lobes are located in field sites where there is more soil cover than rock outcrops. If the glacial ice was flowing east to west, then the Falcon Lake field area would have received relatively more glacial deposits than the other field areas. There is a greater likelihood of solifluction lobes in the Falcon Lake area and this corresponds to the actual findings. Samples from the rock outcrops in the field sites revealed that the solifluction lobes formed in inhomogeneous, iron-free dolomite with a low to medium insoluble content (0 - 20 %). The rock was either coarse or very fine grained but not medium or fine. On investigation, the soil appeared to be a product of glacial deposits as well as the breakdown

of local rock and vegetation. The rocks sampled from the sites of solifluction lobes had either lineations or vugs observable at the hand specimen scale. This indicates that water can certainly travel into the rocks or be stored in the rocks which would aid or maintain the saturation level of the rock. The water could be transferred to the soil and a high saturation level would permit the slow downward movement of the earth causing the solifluction lobes.

5.5 GLACIAL LANDFORMS AND LITHOLOGICAL CHARACTERISTICS

Unmodified glacial landforms only comprise 16.7% of the landforms documented in the Campbell Uplift. They are located most often at the Bottom of Campbell Lake field area. Iron free dolomite, an insoluble content of less than 20%, and inhomogeneous rock are characteristic of the rock on which glacial landforms are found. As with karst landforms, grain size is not a form-controlling factor for the maintenance or development of glacial landforms. The processes involved in glaciation are so large and powerful that the microscopic properties of the rock are likely not as important as sedimentary and tectonic structure, for example, jointing, bedding, or faulting. Glacial processes occur regardless of the bedding characteristics; however, depending on the bedding different landforms may result.

5.5.1 Glacially Plucked/Quarried Surfaces

Glacial plucking in the Campbell Uplift was noted in 3 field sites, all of which are located in close proximity to the fault along Falcon Lake. Since glacial plucking generally occurs on the lee side the location of the plucking indicates that the glacier was moving

approximately from the east to the west. The jointing and fracturing near the fault creates good conditions for quarrying. The rock of the quarried surfaces is type B and has the following characteristics: iron-free dolomite, medium insoluble content (10 - 20%), inhomogeneous, and coarse grained. As well, the plucked surfaces are usually associated with thickly bedded rock that is plucked along the bedding surface leaving behind smooth surfaces parallel to the bedding plane.

5.5.2 Glacially Abraded/Scoured Surfaces

The glacially scoured surfaces in the Campbell Uplift are formed on both dolomite and limestone. 60% of the rock on which they are found has a low insolubility and 70% of the rock is inhomogeneous. It is probable that the first requirement for glacial abrasion, and not simply crushing or grinding, is that the rock be mechanically strong and somewhat massive. This coincides to some extent with the field data but scoured surfaces are also common in areas with thick and thinly bedded rock as well as massively bedded.

After the first requirements, the smaller scale lithological variables such as homogeneity might be important. Grain size of the rock is predominantly fine and very fine for a combined total of 65% of the rock. The scoured surfaces are generally on the eastern side of the field areas and trend in the east-west direction which indicates that the glacier most likely travelled east to west, corroborating the evidence from the quarried surfaces.

5.5.3 Glacial Grooves

Glacial grooves in the Campbell Uplift are found most frequently (54%) on limestone,

then on iron-free dolomite (35%), and finally on ferroan dolomite (11%). This reflects the durability of the mechanical properties of Campbell Uplift limestone over dolomite since the relatively fine sculpture made during glaciation has withstood weathering for approximately 12 thousand years and is still intact and recognizable most frequently on limestone. The rock characteristic of the grooves is inhomogeneous, with a low insolubility (less than 10%) and is fine to very fine grained. In a karst environment, dissolutional destruction of the grooves in these pure rocks might be expected; in the Campbell Uplift, though, the low insolubility has not been of great detriment to the preservation of the glacial grooves. Rock with other properties either did not have glacial grooves or the grooves have since been destroyed by karst or periglacial processes.

5.5.4 Whalebacks

Whalebacks are most often found at sites where the rock is pure (less than 10% insoluble content) dolomite, specifically ferroan, is homogeneous and has medium sized grains. Karst and periglacial processes are noted to act on all rock types defined in this study. Despite this, whalebacks with the above properties have not been significantly modified by the karst and periglacial processes at work in the Campbell Uplift. Therefore, the combination of the rock characteristics and/or topographic location of the unmodified whalebacks are such that karst and periglacial processes do not act as effectively on this type of rock. The larger scale properties of the whalebacks usually include: massive bedding, close proximity to faulting or large cliffs, and lying parallel to the direction of glacial ice movement. The formation of the whalebacks are due to glacial processes, therefore, the rock

properties are important in their preservation and not so much in their formation.

5.6 COMPLEX LANDFORMS AND LITHOLOGICAL CHARACTERISTICS

Complex landforms comprise only a small proportion (16.7%) of the documented landforms in the Campbell Uplift. They are not found in the Quarry and Road field areas and were most often noted in the Falcon Lake field area, 25% of the landforms in this area are complex. Dolomite, either iron-free or ferroan, an insoluble content between 10 and 20%, inhomogeneous rock, and grain size other than very fine are characteristic lithological properties of complex landforms in the Campbell Uplift.

5.6.1 Undercutting

75% of undercutting of rock that was noted occurred in dolomite. Typically, the rock has a medium insoluble content (10 - 20%), is slightly inhomogeneous and tends to have medium to large sized grains. The rock properties of the undercuttings are more typical of rock affected by periglacial activity than by karst processes.

However, topographic characteristics have an important and more dominant role in the location of undercutting of rock. The interface between the rock and vegetation is critical for their development. The presence of standing water is also noted for many undercuttings which supports the hypothesis that this feature develops due to dissolution in the warmer months and frost action when the water freezes. Not all undercuttings have continuous standing water but many do have standing water for at least a week following rain.

5.6.2 Modified Whaleback Forms

5.6.2.1 Slightly Modified Whaleback

The slightly modified whaleback is found in dolomite, more often in iron free than ferroan. Compared to the unmodified whaleback, the rock forming the slightly modified whaleback is more inhomogeneous, typically has a larger grain size, and has a low to medium insoluble content which is higher than for the unmodified whaleback. This is reasonable since the characteristics of the slightly modified whalebacks combine to make it more susceptible to karst and periglacial weathering.

5.6.2.2 V-shaped Valleys

80% of the V-shaped valleys are dolomite (half ferroan and half iron-free) and have an insoluble content of less than 20%. The rock on which V-shaped valleys are found is medium to fine grained and homogeneous. These rock properties are characteristic of the rock that is more often affected by periglacial processes in the Campbell Uplift, hence the modification of the valleys by frost action.

5.6.2.3 U-shaped Valleys

In contrast to the V-shaped valley that forms on smaller grained and homogeneous rock, the U-shaped valley is found predominantly (two thirds of these valleys) in iron-free dolomite that has a medium to high insoluble content, is inhomogeneous, and most often coarse grained. This rock is not typical of the rock that is susceptible to periglacial processes which is further supported by the fact that U-shaped valleys are more often found in massively

bedded rock than thinly bedded (a characteristic of frost shattering). However, surprisingly, the rock properties are only slightly typical of karst processes (iron-free dolomite and inhomogeneity) which are hypothesised to be an important process in their formation. This inconsistency is attributed to the fact that the karst processes are not needed to instigate the formation of the U-shaped valley, unlike grikes, splitkarren, or dolines, and that microscopic lithological properties do not appear to have the most significant role in karst processes in the Campbell Uplift. Therefore, if the rock is already prepared for the establishment of a valley, the rock does not have to be typical of other karst landforms.

5.6.2.4 Modified Whalebacks

The majority of the rock sampled from the modified whalebacks in the Campbell Uplift is inhomogeneous, coarse grained, and iron-free dolomite. The other samples are homogeneous, fine grained, ferroan dolomite. All sampled rock has an insoluble content of between 10 and 20%. Compared to the U-shaped and V-shaped valley rock properties, this landform is most similar to the U-shaped valley and it is hypothesised that these whalebacks will most likely develop into U-shaped valleys if lithology were the most important filter.

CHAPTER 6: SUMMARY AND CONCLUSIONS

6.1 INTRODUCTION

In this final chapter the analysis is concluded by the discussion of the results in terms of karst, periglacial, and glacial landforms in relation to each other. The Landscape Development Model is then presented for microscopic lithological properties and for the sedimentary structure of bed thickness. Since the hypothesis was not originally formulated to include tectonic structures such as joint frequency, data on these were insufficient to include as part of the model. Presentation of the model is followed by a discussion of the success of the model for the Campbell Uplift. A summary of the work and final conclusions are presented in section 6.4.

The aims of this research included: i) the description of the geomorphology in the Paleozoic bedrock of the Campbell Uplift; ii) the determination of the processes and filters that currently operate, and have in the past, to produce the terrain in the Campbell Uplift; and iii) the presentation of these results in the Landscape Development Model. The general hypothesis tested in this report is that the present landforms of the Paleozoic bedrock of the Campbell Uplift developed as a result of both karst and periglacial processes acting upon an inherited landscape mainly of glacial origin, and that these processes are expressed principally through the filter of lithological variation.

These aims have largely been realised: Chapter 4 presents descriptions of the landforms identified in the Campbell Uplift and Chapter 5 explains the processes and filters that are hypothesized to have formed the landforms, be these current (karst and periglacial), in the past (glacial), or a combination (some complex forms). The hypothesis is discussed and judged below in section 6.2. Finally, the Landscape Development Model is applied to the Campbell Uplift in section 6.3.

6.2 DISCUSSION OF THE GENERAL CHARACTERISTICS OF THE LANDFORMS PRESENT IN THE CAMPBELL UPLIFT

The following discussion compares and contrasts the possible combinations of the three main landform groupings: karst, periglacial, and glacial. The complex landform category is omitted here because it has landforms which developed as a result of more than one process. As mentioned in Chapter 5, many of the associations presented by the data analysis are not geomorphologically logical but purely a product of data processing. The relationships that have a known or logical geomorphological basis are likely causal, as discussed below. The danger in dismissing an apparently illogical relationship as random is that an interesting pattern may be ignored; this is why all relationships observed have been faithfully reported in the previous chapter. If relationships that have been dismissed here are discovered in future, more extensive, research, then these conclusions will have to be re-assessed.

6.2.1 Karst and Periglacial Processes

In general, karst and periglacial landforms are found in rock with similar characteristics, although karst landforms will develop regardless of the lithological characteristics whereas periglacial landforms have more specific requirements for development. For example, periglacial landforms are found in rock that has an insoluble content between 10 and 20% while karst landforms occur on both pure (insoluble content of less than 10%) and less pure rock. Karst landforms develop in all soluble rock including limestone but periglacial landforms have a tendency to form predominantly in dolomite.

Periglacial processes require the penetration of water into the rock for its break up. Impurities and vugs allow water to enter the rock and thus facilitate the modification of the rock by periglacial processes. Since large primary holes in, for example, young reef limestone, may also allow entry of water and increase the effects of frost action, the association of periglacial landforms with less pure rock and with dolomite is most likely related to the physical form controlling ease of water access to the rock. Since karst features form equally well in both pure and less pure limestone and dolomite, it is unlikely that the association of rock purity is solely related to chemical composition. Rock purity can be viewed as a form-controlling filter for both periglacial and karst landforms for both chemical and physical reasons.

Periglacial processes act on rock that is fine to very fine grained whereas karst processes are not grain-size specific and karst landforms are evident in rock of any grain size. Grain size is usually directly related to surface roughness and thus to solubility, the optimum grain size for maximum solubility being fine to medium (because the very fine does not allow

any water to get between the grains, it is not very soluble). However, in this region grain size is not as important for karst landforms as other properties, for example, bedding.

A difference between karst and periglacial landforms is that karst processes act more often on inhomogeneous rock and periglacial processes on homogeneous rock. Therefore, where both karst and periglacial processes act in this area, the lithological filter that controls which landform will result is homogeneity. However, this association does not have any obvious logical geomorphological basis and is thus judged to be a non-causal association. The relation is not outstanding and does not need further investigation at the present time.

6.2.2 Karst and Glacial

Karst and glacial landforms develop in rocks that have very similar characteristics: iron-free dolomite, less than 20% insoluble content, inhomogeneous rock, and any size grain. These characteristics are common throughout the study area; therefore, the association of karst and glacial landforms with these properties is probably not causal. If an area has been glaciated then there is the possibility of glacial landforms existing. Similarly, if there is carbonate rock, then karst landforms will more than likely exist. Since the Campbell Uplift is within the limits of the Wisconsinan glaciation and is composed of soluble rock, glacial and karst landforms will likely exist. Since these landforms are present on rock with characteristics general to the rock of the Campbell Uplift, it is suggested that these landforms do not exist because of the rock properties of grain size etc. but due to the presence of carbonate rock and location within the limits of glaciation. Therefore, the only major difference in lithological characteristics of the rock in which both these landforms are found

is that karst landforms also readily form in limestone. Glacial landforms were located on limestone but they are not a dominant feature of this type of carbonate. The fact that both these processes are expressed in rock with similar properties is not unexpected because many karst landforms develop in places that have been prepared (smoothed, levelled, etc.) by glaciers. Also, the karst and glacial processes are not in competition because they have operated at different times in the landscape's development.

In Chapter 2, Background, categories of karst landforms in glaciated terrains were presented and discussed (section 2.7). In the Campbell Uplift, landforms from four categories were identified: types 1 and 2, postglacial, type 6, glaciated karst, and type 7, polygenetic forms. The landforms from type 1 in the Campbell Uplift include surface dissolution forms, precipitate surfaces, solution dolines, stream sinks, collapse dolines, and pinnacle karst, and are landforms that are independent of any glacial forms. Type 2 landforms include features that have developed preferentially due to the effects of glaciation such as pavements and grikes, labyrinth karst, and all forms of slightly and modified whalebacks. Karst landforms that existed prior to glaciation and have been subjected to one episode of glacial erosion (type 6) include large grikes and labyrinth karst. The final form is the collapse resurgence which is type 7, a karst form that has been modified during the glacial period. The importance of classification of the karst landforms present in the Campbell Uplift using this scheme is to document that the forms have a varied history and that they are consistent with other documented karst landforms in glaciated terrains.

6.2.3 Periglacial and Glacial

Periglacial and glacial landforms are found in areas where the rock has some similar and some dissimilar properties. Glacial processes presumably covered a larger area at once than periglacial processes simply due to the power of the glacial processes. The lithological constraints on, or requirements for the formation of glacial landforms are minimal compared to periglacial processes which are more effective in areas with certain characteristics, for example, thinly bedded strata. In keeping with this, glacial landforms are found in rock with a larger range of insoluble content and grain size than periglacial landforms. However, periglacial landforms develop on dolomite in general whereas glacial landforms are present most frequently on dolomite that is specifically iron free. Glacial landforms occur where the rock is inhomogeneous but periglacial landforms are found in both inhomogeneous and homogeneous rock. These last two associations are probably not based on geomorphological processes and are, therefore, not causal.

There is no reason for glacial and periglacial processes to require the same lithological properties to develop. However, periglacial processes may be enhanced by preliminary glacial action, plucked surfaces may allow easier frost shattering and wedging, or these processes may be inhibited by previous glacial action, a polished surface may admit no water for frost action.

6.2.4 Large Scale Properties

The above associations are based solely on the microscopic lithological components. It is important to note that an analysis of sedimentary characteristics, such as bedding, and

tectonic features, such as jointing and faulting, is imperative to the adequate description of the landform development in the Campbell Uplift. The Landscape Development Models presented in the following section detail the microscopic lithological properties *and* bedding characteristics as filters of landscape for this reason. The model attempts to consider the combined effect of these filters. Much of this has been addressed in Chapter 5 because the effect of sedimentary structure is often more specific to individual landforms than to landform categories (karst). However, some general patterns are apparent: periglacial features are more likely expressed on thin beds (frost shattering) while large karst and glacial features are better developed on thick beds (pavements and glacially scoured surfaces); all features are likely to be larger where joint frequency is low (clints); and proximity to faulting raises the hydraulic gradient and causes strong down- and back-cutting (pinnacle karst).

6.3 LANDSCAPE DEVELOPMENT MODEL

The landscape development model is applied to the Campbell Uplift in this section. One aim of the study is to determine the importance of lithology as a filter of landform. This section addresses this question by presenting the model in Figures 6.1 to 6.5. The microscopic lithological properties are presented first and then the larger scale characteristic of bed thickness for a more complete understanding of the components that influence the landscape of the Campbell Uplift. (As explained above, section 6.1, data were not collected on the tectonic structures). The associations identified indicate that different processes act in the study area but form specific features only when certain criteria are met, when specific characteristics of the filters are present.

Note: in Figures 6.1 to 6.5 K, P, G, C stand for karst, periglacial, glacial, and complex landforms respectively. The landforms are those found in the Campbell Uplift only.

Figure 6.1: Carbonate rock type as a filter in the Landscape Development Model for the Campbell Uplift

Figure 6.2: Insoluble content as a filter in the Landscape Development Model for the Campbell Uplift

Table 6.3: Homogeneity of the rock as a filter in the Landscape Development Model for the Campbell Uplift

Figure 6.4: Grain size as a filter in the Landscape Development Model for the Campbell Uplift

The results of the associations identified from the data are presented in the Landscape Development Models above. Unfortunately, the associations are not necessarily causal and do not completely explain the presence of specific landforms. Glacial features will, for example, modify most rock types and, therefore, the control of rock type, insoluble content, homogeneity and grain size on glacial landform *development* is basically irrelevant. However, the *preservation* of glacial features may depend on these microscopic characteristics and the relations presented in the models are not discarded for this reason. Lithology is generally considered to represent the chemical and physical composition of a rock at the hand-specimen scale or smaller. Therefore, it is necessary to expand the idea of lithology or rock properties to sedimentary structure, specifically the larger scale property of bedding, to try to explain the morphologies and features present in the Campbell Uplift.

Figure 6.5: Bedding as a filter in the Landscape Development Model of the Campbell Uplift. The landform categories indicated are not exclusive but the most dominant as all landform categories are represented by each bedding type.

In light of the analysis based on established geomorphological properties, the extension of lithology to include sedimentary structure, specifically bedding, is still insufficient to explain all the features and morphologies of the study area. This is not unreasonable since landform development requires the synthesis of many different influences, such as chemical and physical properties of the rock, sedimentary structure, climate, and time, for the complete expression. Therefore, tectonic structure, including the characteristics of jointing and faulting, and topographic situation, specifically influencing the hydraulic gradient, must also be considered if a complete analysis of the factors that control landform development is to be completed of the Campbell Uplift. However, this essentially means that microscopic lithological properties of the rock in the study area can not be considered to be the form controlling components of the landscape.

The models presented in Figures 6.1 - 6.5 are not all encompassing. They do not include specific characteristics of all the features encountered in the study area, only the general characteristics of the four categories of landforms based on dominant forming process. Many features cannot be explained by the above models due to the scale of the processes defined (karst dissolution in general and not specific to pavement development, for example). Specific characteristics that are relevant to only some landforms, slope form, for example, are not considered in the models. The models do not replace the discussion of each individual landform but serve to present generalised information on each general landform category. The specific landform characteristics are discussed in the analysis of the landform characteristics (Chapter 5, Analysis) and are summarized in the following section (6.4).

The landscape development model presented is solely based on the data collected from

the Campbell Uplift study area. However, the model should be applied to other carbonate areas to test its applicability as a universal arctic karst model.

6.4 FINAL SUMMARY

The general hypothesis is that "the present landforms of the Paleozoic bedrock of the Campbell Uplift developed as a result of both karst and periglacial processes acting upon an inherited landscape mainly of glacial origin, and that these processes are expressed principally through the filter of lithological variation". Each component of this hypothesis is discussed below in turn.

This study has shown that landforms in the Campbell Uplift are dominantly the result of both karst and periglacial processes: the result of these two processes comprise two thirds of the landscape. The other third is equally divided between glacial and complex landforms. The landforms documented in the Campbell Uplift are summarised in Table 6.1 (p.189).

The expression of these processes through the filter of lithological variation was tested by comparing landform presence and property with lithology. Lithological variation was studied because previous authors have suggested that it is an important control on landform development. For example, Sweeting identified lithology, mainly grain size, as a control factor in pavement development in England (Sweeting, 1973, p.184). Another example is from the study by Wilford and Wall (1965) of the karst in Sarawak. They identified lithological properties of purity and low primary porosity, as well as structural properties of massive bedding and widely spaced jointing, as factors important in assuring mechanical strength necessary for limestone cliff formation. Therefore, the different filters present in the

Campbell Uplift that were considered in this study included some micro- and macro-scale properties of the lithology. The results were assessed in light of geomorphological reason and the conclusion reached that the most important filter governing the characteristics of a landform is not necessarily a microscopic property of the lithology but rather the larger-scale rock properties. Many associations make geomorphological sense and appear to be reasonable; some associations seemed to be random and not based on geomorphological principles. A summary of the most important filter for each landform is presented in Table 6.2.

Table 6.1: Type and proportion of landforms documented in the Campbell Uplift

Category	Proportion	Specific Landform Features
Karst Landforms	33%	Microkarren, cockling, splitkarren, grikes, shillow - free pavements, shillow pavement, labyrinth karst, pinnacle karst, solution dolines and stream sinks, collapse dolines, collapse resurgence, precipitation
Periglacial Landforms	34%	Frost shattered forms, frost wedged forms, frost pockets, solifluction lobes
Glacial Landforms	16.5%	Glacially plucked/quarried surfaces, glacially abraded/scoured surfaces, glacial grooves, whaleback(unmodified)
Complex Landforms	16.5%	Undercuts, slightly modified whaleback forms, V-shaped valleys, U-shaped valleys, modified whalebacks

This study of the geomorphology of the Campbell Uplift suggests that the macroscopic properties of sedimentary and tectonic structure are equally important and potentially even influence landform development to a greater degree than the microscopic properties of lithology. This conclusion does not mean that microscopic properties studied

herein do not influence landform development, only that they are not the most important in their formation, not the form-controlling filter. Sedimentary structure, and jointing, fracturing, and bedding, in the Campbell Uplift dictate to a large extent what landform has developed. Topographic situation is important in a few cases.

Table 6.2: The form-controlling filter for each landform in the Campbell Uplift

Landform	Filter	Landform	Filter
Microkarren and cockling	lithology for form only	Frost wedged forms	fine grained limestone
Linear form karren - splitkarren	joints, veins, micro-fractures	Frost pockets	presence of water, massive bedding
Linear form karren - grikes	existence of pavement	Solifluction lobes	lineations or vugs
Shallow - free pavements	pure dolomite and limestone	Surfaces glacially plucked/quarried	jointing or fracturing
Shallow - pavement	massive bedding	Surfaces glacially abraded/scoured	massive bedding
Labyrinth karst	faulting, jointing, massive bedding	Glacial grooves	limestone
Pinnacle karst	massive bedding, process	Whaleback (unmodified)	direction of ice movement
Solution dolines and stream sinks	topographic position	Undercuts	topographic position
Collapse dolines	proximity to cliff	Slightly modified whaleback	lithological properties
Collapse resurgence?	topographic position	V-shaped valleys	lithological properties
Precipitation surfaces	micro-climatic variables	U-shaped valleys	prepared by previous processes
Frost shattered forms	thickness of bedding	Modified whalebacks	process

6.5 FINAL CONCLUSIONS AND IMPLICATIONS

From the evidence presented, it is concluded that lithology is not the only filter but is important at the individual landform level for some features. Different lithological properties are associated with landforms attributed to a specific (or more than one) process, although they are not necessarily causal relations. In Figure 6.6, the general landscape of the Campbell Uplift is explained in terms of the Landscape Development Model. Glacial landforms are an inherited form that itself acts as a filter when they are presently acted upon by karst and periglacial processes. The rock properties defined as the filter include sedimentary structure as well as the properties discussed in detail in this thesis such as grain size, rock type, and insoluble content. The landforms that result are due to the actions of karst dissolution and periglacial frost-related processes acting on various lithologies and sedimentary structures.

N.B. "+" means combination of the rock properties and sedimentary structure and the glacial landforms to act as a new filter of landscape processes

Figure 6.6: General Landscape Development Model of the Campbell Uplift beginning with the effects of the Wisconsin Glaciation

The implication of this conclusion is that the harder-to-study, large scale features (bedding, topographic situation) are more important and valuable to study in the future than the properties studied from hand specimen samples that are easily studied in a laboratory situation, removed from the field. A benefit of this implication is that researchers will be encouraged to spend time doing field work. Studying geomorphology in the environment may foster a greater awareness of the many different components of an environment that combine together to create landscape which may be more effective than trying to gain this awareness through study removed from the actual study area. This in turn may promote geomorphology as an important component of the ecosystem and not some foreign theoretical

concept that may be disregarded when assessing the value of an area, for example, in an environmental assessment.

Another implication of this thesis is that more systematic quantified study needs to be completed for an encompassing explanation of the landscape development history in the Campbell Uplift. The data, specifically the line transect data, are presented in hope that future studies can be completed wherein the researchers use this information to supplement their findings. In doing this, new ideas and increased sample size could combine to permit future researchers to identify associations that were discarded or to support the conclusions made herein. A final note is that the data gathered and discussed in this thesis are also presented in hope that they will serve as baseline data for study of *other* field areas that are located in arctic karst environments *and* for general geomorphological study of an area. The data presented are kept on computer file and with the widespread use of computers could be easily transmitted to other researchers anywhere in the world thus promoting data distribution for increased co-operation in scientific research.

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APPENDIX A: LINE TRANSECT DATA

The line transect data is presented in tables and with graphs. The information in the tables corresponds to the line segments on the graphs. In total there are 23 line transects for the Campbell Uplift. The tables present information from field notes and include many abbreviations for the features noted. A key to the abbreviations used is presented below.

Abbreviation	Form
c	cockling
c&g	clint and grike
dis.	dissolution
e	erratics
fp	frost pockets
fs	frost shattering
fsd	frost shattered debris
fw	frost wedging
gd	glacial deposits
gg	glacial grooves
jk	joint karren - structural karren
gm	glacial material
sk	structural karren
spk	split karren
sw	standing water
u	undercutting

Transect 1 - Falcon Lake - Area 2 to Area 3

203

Section	Notes	
1.0	whaleback	
7.6	jk,dis	
12.0	whaleback	
25.2	sk	
31.4	whaleback	sample I-I
32.4	c,jk,sk	
42.8	c,sk,sw	
51.9	wet	
56.1	sk,c,dis,u	
62.8		
65.6	fs	
84.8	whaleback	
92.8	sitting pond of water	
94.3		
99.8	sk,dis	
105.8	whaleback	
124.8	sw	
124.8	u, frost pocket	samples I-II,III,IV
129.4		
151.9		
181.6	sk,fs	
190.8		
193.7	sk,jk,c&g	whaleback
197.0	gg,c	sample I-V
212.0		
212.0	c,jk,sk,lots of dis.	
216.4	e,needle ice heaving	
216.4		
216.9		
216.9		
222.1	fs,gg,pitting, rounded clints	
222.1	jk,fs,c,u	
228.9	water/swampy	
231.6		
233.8	c&g, jk	
239.6		
243.4	dis	

Transect 2 - Falcon Lake - Area 4 to Area 5

204

Section	Notes	
7.5	g, spk, dis	High hydraulic gradient - rocks pushed "easily"
14.5	g	
17.5	frost pocket	sample V-I
22.8	dis of boulder pile	
23.5	gg, uc, sk, sw	
27.1	spk, whaleback	sample V-II
29.7	dis, u	plucked
40.2	plucked block 5m downslope	
41.7	c, jk, small fs	
45.7	plucked	
52.4	c&g, spk, w of c&g	
53.2	dis, c	
58.9	sw, flowing water	
59.6	c, sk, jk	

Transect 3 - Falcon Lake - Area 7

Section	Notes
0.0	fs of thin beds, c on massive beds
14.5	e, fsd
16.2	vugs opened by dis, fsd
24.0	sk, c
27.1	small outcrop
43.7	fsd, solifluction lobe - sample VII-I (just above G)
51.8	sk, vuggy, fsd, fp - material fs then dis
54.0	dis, some sorting of blocks
54.9	solifluction lobe
81.5	solifluction lobe
108.3	gm, gddis
122.2	g

Transect 4 - Falcon Lake - Area 5 to Area 6

Section	Notes	
1.0	dis,u,sw	
6.2	u,sw	
8.4	collapse, dis of fp	
16.6	dis then fs,e,c&g	whaleback
20.5	fs,gg,dis	
24.6		
28.3	fsd	
33.9	c.sk	
41.2	c&g,sk,spk,dis,gd	whaleback
43.4	fs,u,water, hydrothermal calcite?, brecciated	
48.0	uc, dis, sw	
52.7	gg,sk,c, reefal zone?	
60.1	dis,sk,fs,c&g	whaleback,plucked
61.1	sk,c,uc,sw	
66.3	uc,sw	
68.1	sk,dis	
76.0	dis, c&g	plucked
76.5	sk,c,vuggy	
86.4	gd,dis then w	plucked

Transect 5 - Falcon Lake - Area 7 to Area 8

Section	Notes	
29.6	rock patches	solifluction lobe
54.7	veg covered talus	
74.5	fw,dis,rock slab talus	
90.3	vuggy,pitted,scoriated	
109.1	g venear,sk,c	"whaleback-to-be"
131.0	gd,sk	
149.1	spk,dis,gd,bedding 22' parallel to slope	
159.5	g venear,vuggy	
166.1	vuggy	
184.4	no exposed rock, veg	
188.5	" "	
200.4	" "	
200.9	tiny u	
205.1	dis,c&g	whaleback
205.5	c	

Transect 6 - Falcon Lake - Area 11

Section	Notes
0.0	c&g,sugar stone,brecciated calcite pocket
1.2	c&g,sugar stone
2.6	fs talus,gg
10.1	
11.6	c,sk,tiny pinnacles
12.7	gg
13.7	
16.5	sk,sugary whaleback
19.8	gg,sk,dis,sugary
32.8	sk
36.7	collapse blocks, gg, brecciated
42.2	
46.2	sk,c&g,gd
49.6	dis,vuggy frost pocket
51.6	
55.0	" "
65.5	gd,sk,c&g
69.1	gg,fsd,c,sk,talus mantled rock
70.8	
70.8	
74.1	sk,c&g(cov.byveg),
75.5	sk, 1m of u,fs,w
78.7	
80.2	1m of u

Transect 1 - Bottom of Campbell Lake - Area 3

Section	Notes
25.2	blocky scree,fsd
28.1	little size scree
32.9	dis
32.9	giant grike?
33.1	
33.1	
33.1	gd

Transect 2 - Bottom of Campbell Lake - Area 3

207

Section	Notes	
2.6	sk,gd,c	
29.8	gd,sk,dis,c&g	pavement
31.0	u,wet	
86.0		
88.7	c,dis,sk	frost pocket
117.4	gd,e	recently cleared pavement

Transect 3 - Bottom of Campbell Lake - Area 6

Section	Notes	
8.3	fsd at base	
9.1	gd	
9.3	sk,d,smallgg	
8.8	dis,fsd	
7.8	sk	
6.9		
7.8	not much fsd	
12.8		
12.1	gd	(sample VI-II - more massive rock)
10.1	dis, u	
10.4		frost pocket
15.2	jk,sk, dis holes	sample VI-I

Transect 4 - Bottom of Campbell Lake - Area 7

Section	Notes	
4.1	gd,e	pavement
15.0	" "	pavement
19.4	dis, sk	
27.8		
31.5	gd,dis	

Transect 5 - Bottom of Campbell Lake - Area 8

208

Section	Notes	
3.8	dis,c,sk	
14.4	u	
14.5	sk,dis	
18.2	unmodified whalebacks	
35.5		
40.0	dis	
42.8		
44.1	lots of surface dis	
56.4	gg on pvt,sk,dis	pavement
61.6	u	
102.6	gd	sample VIII-I
102.9	u, water	

Transect 6 - Bottom of Campbell Lake - Area 10

209

Section	Notes	
1.5	fsd,massive rock	frost pocket
6.9	fsd,dis	
6.9	fsd,cappt,massive rock	
10.7		
10.7		
19.5	fsd,dis	
28.7	fs,c,massive rock	
28.7	fs	
39.3	veg	
44.8	u,fsd,massive rock	
49.3	fsd	
51.0	fs,dis	
55.1	fs,gd	
57.4	fsd	
59.6	fsd, gd	
61.2	fsd,dis,c,old sk	
64.4		
74.4	gd	
77.8	dis,fsd,c	whaleback
78.5		
79.9	fsd	
81.4	fsd,(nice)dis	
86.9	fsd,sk,gd,dis	old whaleback?
88.3	ca bits, inhomrock	sample F-1
91.8	fsdscree,dis	
100.1		
100.5	fsd/surf	
103.7		
105.6		
106.9	fsd,dis	
111.1	gd,gg	whaleback
116.2	fs,dis of fsd	
127.2		
129.6	fsd,dis,massive rock	
142.8	gg,sk,dis	

Transect 1 - Middle of Campbell Lake - South Side - Area 7

210

Section	Notes	
10.1	fsd,gd	
12.2	inhom.massive bed	
20.8	jk,fs,w,dis,spk,gd	pavement-shallow
25.0	jk,spk	
30.2	gd,small fsd	
36.3	fsd	
41.5		
45.5	fs(ca)d	
46.8	jk,sk,ca bed	
55.2	gd,fsd,e,sk	
64.1	gd	
75.5	sk,gd	shallow
87.8	gd	
98.2	spk,gd,massive r	pavement
108.6	gd	pavement

Transect 2 - Middle of Campbell Lake - South Side - Area 6

Section	Notes	
2.6	dis,fs,jk	solifluction surface
6.8	spk,fsd	
8.9	e,gd	
13.4	c,spk,sk	pavement
14.2		sample VI-I
15.7		
15.8		
20.8	c,fs,sk,spk	
22.0	c,jk,not much fsd	

Transect 3 - Middle of Campbell Lake - South Side - Area 8

211

Section	Notes	
3.9	fsd,gd	
10.3	gd	
18.3	c&g,spk,e,bitof fsd	pavement
25.6	gd,fsd	
34.1	gd,fsd	
62.5		
63.6	blocky fsd	
67.1		
78.0	gd,e	
84.7	scree	
112.8	fsd, thinly bedded	sample VIII-I

Transect 4 - Middle of Campbell Lake - South Side - Area 9

Section	Notes	
7.6	fs,ca,30cm beds	frost pocket
25.5		sample IX-I (a-b)
31.3	fsd, thinly bedded	
39.3	gd, flat	
43.3	sk	

Transect 5 - Middle of Campbell Lake - South Side - Area 11

212

Section	Notes
3.7	fsd(small),gd
5.3	inhom"beds",Ca
13.7	
16.5	inhom"beds"/massive
19.5	very fs
21.5	not much scree
26.8	" "
29.5	massive. Ca.inhom.
35.6	
38.1	
57.7	small bit of talus at base
62.8	gd
72.5	
73.6	thinly bedded, not much fsd
79.2	gd
80.0	u
83.0	
84.1	fsd, thinnly bedded
88.1	gd
89.2	fsd
95.7	
98.5	fsd(small)

Transect 1 - Middle of Campbell Lake - North Side - Area 15

Section	Notes
4.9	dis,fs,bedding: 1m&40cm
22.2	gd,e,smallfsd,not much dis shallow
25.1	dis.fsd,same bedding as a-b
27.4	level talus
29.6	dis, sim bedding to a-b
39.3	gd,e,smallfsd,not much dis shallow
41.5	jk,sk,sim bedding to a-b
47.2	
49.0	jk,sk,sim bedding to a-b
52.3	gd,e,smallfsd,not much dis shallow

Transect 2 - Middle of Campbell Lake - North Side - Area 16213

Section	Notes
30.0	
36.8	fsd, big slabs bare r exposed
38.6	fsd, u of thin beds, beds 20cm 30cm 60cm
40.5	
42.9	fsd
54.2	gd, fsd (10x10x5cm)
57.5	fs chunks (3x2m), beds 1-2m, Cappt
62.0	u sample A-4 (g-h)
62.4	samples A-2, 3
78.8	small fsd, dis, gd
83.6	dis, c, dis. on joints, beds 1-1.7m, fine grained
85.6	small fsd
87.3	dis, c, dis. on joints, beds 1-1.7m, fine grained
98.4	gd, 40cm joint
105.8	

Transect 3 - Middle of Campbell Lake - North Side - Area E

214

Section	Notes
15.6	medfsd covered in veg,dis,thinlybedded
22.1	smfsd&gd on ledges20x20cm,dis,bedding 20-40-65cm
28.8	gd
31.5	bed+/-20cm,gd,jk,sk,dis,fsd,v.weathered
53.9	gd,dis,sk
62.5	dis.ofsm/med.scree,gd
62.5	dis,Ca,beds20-30-50cm sampleE-8
66.1	
71.0	dis,jk,fsd,beds70cm
81.8	gd,sm.fsd
98.6	tinyfsd,sm/med.gd
119.3	grikes4mdeep,30-50cmwide grikes/bogas
119.3	finegrained,hom,dis,fsd,
147.2	sm-boulder fsd
147.2	fs,dis,massive blocks w/sm stuff
157.9	e,sm.fsd,gd sample E-9 (o-p)
161.6	sm.fsd,gd
176.5	sm.fsd,gd scoured?
189.5	sm.fsd,gd scoured?
199.2	sm.fsd,gd scoured?
222.4	sm.fsd,gd scoured?
223.6	dis,jk,sk,
225.1	u (base of v-w)
225.1	
225.8	
233.8	w,sm&bigfsd
233.8	dis,fsblocks of scree

Transect 4 - Middle of Campbell Lake - North Side - Area G

215

Section	Notes	
2.5		
28.4	gd,v.v.sm.-sm.fsd	
35.2	gd,tinyfsd	
38.2	dis,fsd,beds 1 m	
47.6		
50.6	dis,sm.fsd	
69.6	gd,tiny-sm.fsd	
84.9		
88.2		
94.1	fsd,gd	
103.3	gd,v.v.flat	
106.5	60cmdeep,small valley	
123.8	sm.fsd,gd	
124.9	dis	
127.5	plan view - part of v-shaped valley	
131.0	tiny-sm.scree/fsd	
136.7	gd,flat,tinyfsd	whaleback
137.8		
142.2	valley w/ veg	
146.1	tiny-sm.fsd	
155.9	patches-gd,tinyfsd	whaleback
158.6	10cmdeep veg valley	
173.4	gd,tinyfsd,flat	whaleback
176.2	40cmdeep veg valley	
190.6	tinyfsd,gd,flat	whaleback
194.1	tinyfsd,no veg	
206.7	tinyfsd,no veg	
206.7		

Transect 1 - The Quarry - Area Q-1

216

Section	Notes
13.7	fs,w,gd
25.1	tinyfsd
29.3	tinyfsd,some blocks
35.1	tiny-med.fsd
56.3	hardly any rock
82.1	" "
87.5	
94.1	blocksfsd.dis,jk
102.0	fsd,gd
116.4	massive fw blocks
133.8	more blocks

Transect 2 - The Quarry - Area Q-2

Section	Notes
0.0	scree
4.0	dis,sm.fsd
7.4	gd
11.5	wedged r from e-f
24.3	sfsd,dis,lg.fw along bedding
33.2	gd,sm.fsd,spk,jk,dis
40.4	gd,sm.fsd,fw of lg.blocks old pavement
43.6	fw,fs,dis
60.5	veg valley
70.5	talus of v.v.v.fsd(fine sand),thin beds then thick at top of slope
76.7	sm.fsd old pvt, whaleback
84.5	lg.fw blocks cov/d w/ veg
96.9	veg valley
104.9	gd,sm.fsd(like sand),fw blocks
118.8	sm.fsd old pvt, whaleback
134.0	veg valley
141.3	bedded sample Q-1
150.6	sm.fsd(starting),spk,gd pavement -shallow starting
170.4	
186.0	veg valley
199.1	lg.fw blocks -talus tongue
204.9	fw blocks,dis, 1-2mm ppt, steps in slope
217.4	gd, smooth surface
223.4	"slate" med.fsd
225.7	fw blocks,dis,fsd pavement

Landform	Location	Height	Width	Length	Surface Characteristics
slightly mod w/b	FL-2		3m	17m	parallel ridges, lots of m/k, veg btw ridges
u-shaped valley	FL-3	5-8m	17m		valley really wet, m/k vertical slope, bedded 60cm, uc
u-shaped valley	FL-3	3-6m	4.75m		bedded 2-2.5m, 10-20-35cm, Ca, fsd at base
mk	FL-3	finger print size			
solifluction lobes	FL-7	22* angle			
frost pocket	FL-7				
solifluction lobes	FL-10	35*angle, 10*"horizontal"			
frost pocket	FL-10	80cm, 15cm	60cm(widest)	3m+	pocket bends to left - dissolution?
fsd	BCL-3	1mx50cmx50cm, 20cmx20cmx20cm			
weathered rock	BCL-5	15,20,30cm	10, 15cm; 3-4cm diameter		massive, inhomog., little holes everywhere
collapse	BCL-9	0.9m	2.8m	1.7m	35*slope into earth at undercut - 1.4m deep
collapse	BCL-2	1.3m	4m	4m	undercut into corner 70cmwide, 2.2mdeep, 75cmhigh
collapse	BCL-2	1.35m	1.7m	3.7m	no undercut visible, bedding 20-25-35-40cm
collapse	BCL-2	1.1m	2.6m	8.3m	no visible undercut
collapse	BCL-2	60cm	1.2m	2.2m	undercut - 1.1m deep
shallow pvt	BCL-1				80cmbedding and massive on top, fsd 2x2cm, 5x8cm,
frost pocket	BCL-12	90cm, 90cm	1.7m, 1m	3.1m in	60cm, 1mbedding, massive on fp side, fsd lining bottom
pvt	SS-6		5m	10m	sk (80cm long, avg 3cm wide)
frost pocket	SS-9	1m	1m	1m	fsd at base
old pvt	SS-9	-18*to-4.5*angle 12m		51.4m	massive rock, gd
undercut	SS-9	60cm	1m	1m	massive rock
frost pocket	SS-10	35cm	40cm	1.8m in	massive, ppt. on overhang, fs surface above dis.
frost pocket	SS-10	59cm	60cm	90cm	massive rock
frost/dis'n pocket	SS-10	1.3m	40cm	2m in	massive, Ca patches&veins, talus/fsd at base
NS 43 grike	NS-1	2.5m	60-68cm	7.8m	uc at diff. levels, veg/soil at base, smpl 50cm from surface
uc	NS-13	0.3m	0.5m	base	massive bed 2m, 45cm, 4.3m, 1.2m

Landform	Location	Height	Width	Length	Surface Characteristics
fsd	NS-13				from thinly bed more than massive
frost collapse	NS-14		3.2 50cm	6.2m	fsd at base
fsd	NS-20				from 10-25cmbeds,
uc	NS-20			0.7m+	from 10-25cmbeds,
fsd	NS-19				
sink	NS-17/D				thinly bedded near surface
fsd	NS-18	1.2m, 1.8m, 40cm, 1.3m, 20-60-20-80cm			thin beds fs(A-6), thick-more dis.(A-5)
scour	NS-A				
shallow	NS-A	3x2x1cm, 10x30x20cm, avg. 3x2x1cm - fsd			
outcrop	NS-B btw 2 depressions				thin to med. beds
fsd	NS-C	40cm, 1m, 1.2m, 1.2m, thin, thin, thick...			thin bed -Ca, homog. rock, thick bed - inhom. rock
sink	NS-F	2.2m outcrop near sink			thinly bedded at base
uc	NS-F	2m	2m	3m into	thinly bedded
us	NS-H				
corridor karst	NS-G				
fsd	Q-A-1				
fw	Q-A-1				
gd, erratics	Q-A-1				
Ca on rocks	Q-A-3				
shallow	Q-5				Q*M-1,2 Ca - 2mm thick coating
fw	Q-5	50cm	50cm	80cm	gd on pvt, sk, fw covered in Ca paint
structural karren	Q-5				
ppt	Q-5				2mm thick on joints and fw/s surfaces, paint
beginning doline	Q-5	2.2m	80cm	2.1m	soil at bottom, fsd inside, fs sides

Transect 1 - Falcon Lake - Area 2 - 3

Transect 1 - Falcon Lake - Area 2 - 3

Transect 1 - Falcon Lake - Area 2 - 3

Transect 1 - Falcon Lake - Area 2 - 3

Transect 1 - Falcon Lake - Area 2 - 3

Transect 2 - Falcon Lake - Area 4 - 5

Transect 3 - Falcon Lake - Area 7

Transect 3 - Falcon Lake - Area 7

Transect 3 - Falcon Lake - Area 7

Transect 4 - Falcon Lake - Area 5 - 6

Transect 4 - Falcon Lake - Area 5 - 6

Transect 5 - Falcon Lake - Area 7 - 8

Transect 5 - Falcon Lake - Aea 7 - 8

Transect 5 - Lake Falcon - Area 7 - 8

Transect 6 - Falcon Lake - Area 11

Transect 6 - Falcon Lake - Area 11

Transect 1 - Bottom of Campbell Lake - Area 3

Transect 2 - Bottom of Campbell Lake - Area 3

Transect 2 - Bottom of Campbell Lake - Area 3

Transect 2 -Bottom of Campbell Lake - Area 3

Transect 3 - Bottom of Campbell Lake - Area 6

Transect 4 - Bottom of Campbell Lake - Area 7

Transect 5 - Bottom of Campbell Lake - Area 8

Transect 5 - Bottom of Campbell Lake - Area 8

Transect 6 - Bottom of Campbell Lake - Area 10

Transect 6 - Bottom of Campbell Lake - Area 10

Transect 6 - Bottom of Campbell Lake - Area 10

Transect 1 - Middle of Campbell Lake - South Side - Area 7

Transect 1 - Middle of Campbell Lake - South Side - Area 7

Transect 2 - Middle of Campbell Lake - South Side - Area 6

Transect 3 - Middle of Campbell Lake - South Side - Area 8

Transect 3 - Middle of Campbell Lake - South Side - Area 8

Transect 4 - Middle of Campbell Lake - South Side - Area 9

Transect 5 - Middle of Campbell Lake - South Side - Area 11

Transect 5 - Middle of Campbell Lake - South Side - Area 11

Transect 1 - Middle of Campbell Lake - North Side - Area 15

Transect 2 - Middle of Campbell Lake - North Side - Area 16

Transect 2 - Middle of Campbell Lake - North Side - Area 16

Transect 3 - Middle of Campbell Lake - North Side - Area E

Transect 3 - Middle of Campbell Lake - North Side - Area E

Transect 3 - Middle of Campbell Lake - North Side - Area E

Transect 3 - Middle of Campbell Lake - North Side - Area E

Transect 3 - Middle of Campbell Lake - North Side - Area E

Transect 4 - Middle of Campbell Lake - North Side - Area G

Transect 4 - Middle of Campbell Lake - North Side - Area G

Transect 4 - Middle of Campbell Lake - North Side - Area G

Transect 4 - Middle of Campbell Lake - North Side - Area G

Transect 1 - The Quarry - Area - Q-1

Transect 1 - The Quarry - Area Q-1

Transect 1 - The Quarry - Area Q-1

Transect 2 - The Quarry - Area Q-2

Transect 2 - The Quarry - Area Q-2

Transect 2 - The Quarry - Area Q-2

Transect 2 - The Quarry - Area Q-2

Transect 2 - The Quarry - Area Q-2