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GEOMORPHOLOGY OF THE CORONATION-SPONDIN SCABLAND

BY

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THE UNDERSIGNED CERTIFY THAT THEY HAVE READ, AND RECOMMEND TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH, FOR ACCEPTANCE, A THESIS ENTITLED, **GEOMORPHOLOGY OF THE CORONATION-SPONDIN SCABLAND.**

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ABSTRACT

Traditionally, spatially discontinuous channel networks on the Canadian Prairies are interpreted as having formed subaerially in front of a retreating glacier. Evidence in the Coronation-Spondin scabland, east-central Alberta, suggests an alternative formation by progressive channelization of a subglacial sheetflow. The channelization period occurred during the waning stages of the hypothesized, Livingstone Lake sheetflood "event". That the channels were formed after peakflow of the Livingstone Lake "event" is indicated by the truncation of giant flutings at Sheerness.

The Coronation-Spondin scabland is an integrated channel network that displays varying degrees of anastomosis. Channels have highly variable sizes and orientations. Enhanced scour at channel confluences suggests contemporaneous channel utilization. Channels also display convex-up, concave-up, and undulatory along-channel profiles with junctions at the same elevation. Longitudinal grooves are observed in large-scale channels and are associated with numerous boulder lags. Residual hills, demarcated by channels, display curved, polygonal, and streamlined forms. Superimposed on residuals, are ripple forms, longitudinal grooves, and undulating surfaces that indicate submergence for all but the last phase of channelization. This phase was characterized by recoupling of an irregular ice roof onto a saturated substrate. This recoupling was responsible for small-scale glaciotectonic features and highly deformed till.

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E OF CONTENTS

LIST OF FIGURES

CHAPTER ONE: INTRODUCTION

PROBLEM STATEMENT

Alberta has been subject to at least two glaciations over the course of the Pleistocene (Roed 1975). These involved both Cordilleran and Laurentide ice sources. Resulting from these glaciations are vast tracts of glacigenic landforms, ranging from those associated with proglacial environments to those which originated subglacially. Landform suites are seldom easily delineated but, rather, occur in melanges of several, nested, genetic types. This landform heterogeneity is illustrated by Quaternary geology maps of central and southern Alberta (Shetsen 1987, 1990), indicating that some proglacial landform-sediment complexes have in places truncated or completely masked previously developed subglacial landforms (such as giant fluting tracts). With respect to possible formative processes, interpretation of such mixed landform suites is often difficult.

There are two plausible hypothetical explanations for the creation of the channels and residuals that are the focus of this study: the first is that they were formed proglacially by water under gravitational potential; the second is that they were formed subglacially by water under hydrostatic pressure. Both theories have positive aspects in explaining the formation of meltwater channels. A proglacial stand has been taken to interpret spillways in other areas of the prairies (Kehew 1982, Clayton 1983, Kehew and Lord 1986, Teller 1990) and subglacial meltwater has been the hypothesized causative erosional process for some areas of scoured bedrock (Sharpe and Shaw 1989). It is the relatively new concept of subglacial sheet flows, with varying degrees of channelization, that will provide an alternative hypothesis to that which has long been established in the glacial spillway literature.

Glacial meltwater channel forms have been classically assigned to ice marginal and/or proglacial environments, often involving jökulhlaup-like floods of water (Baker and Bunker 1971, Kehew 1982, Clayton 1983, Kehew and Clayton 1983, Teller and Thorleifson 1983, Baker 1985, Kehew and Lord 1986, Teller 1987). Spillway channels are believed to have been created by floods of open-channel water released from one glacial basin to another at a lower elevation (Kehew and Lord 1989). The assumption that flow was largely controlled by gradient is justified only in those cases where flow was demonstrably subaerial, but this was not the case where flow was subglacial (i.e., introduction of hydrostatic pressure as the primary driving force).

Aspects of inter/intrachannel morphology are of primary importance for interpreting the paleohydrologic conditions at the time of formation. Kehew and Lord (1986) presented an in-depth discussion of channel morphologies and concluded that channel evolution begins with broad shallow flows "broken" by large residual "islands". Subsequently the "islands" are modified by increased channelization, truncation and residual elongation. They concluded that lemniscate residual forms approximate the equilibrium condition where frictional drag is minimized, and the ratio of maximum residual width to length appears to be the most representative measure of this condition. The erosional streamlining effect that creates the lemniscate form is noted to be most effective if the residual is submerged in the flow (Kehew and Lord 1986). In addition to their observations on residual "island" morphology, they speculated that longitudinal vorticity results in inner-channel incision by the convergence of these vortices. From the spillway literature it appears that subaerial paleohydrology may have analogies in the subglacial environment.

In recent years another hypothesis has engendered speculation on the origin of fluvial landforms, especially those related to subglacial sheet flows (Shaw 1983, Shaw and Kvill 1984, Shaw *et al.* 1989). A major strength of this "subglacial flood hypothesis" is its applicability to topographically high areas that could not have been significantly affected by subaerial flowing water. Subglacial hydrostatic pressure might provide the means by which water could, conceivably, flow over such "highs". The landforms created by these floods range from small-scale erosion marks, in the order of centimetres long (Shaw 1983), to those at the scale of kilometres (Shaw and Kvill 1984). It is to be expected that flows creating such landforms would have been of highly varied scales.

This conceptualization of scales immediately raises questions about probable water sources. Proglacially, large quantities of water were available in dammed ice-marginal lakes (Kehew 1982, Clayton 1983). Evidence of large subglacial quantities of water is much less obvious. Investigations of glacier-bed conditions under the polar Antarctic ice sheet have revealed substantial quantities of water (Oswald and Robin 1973). In the temperate glacier environment that probably typified the south-western Laurentide ice sheet, glacier-bed conditions would have been largely wet-based (Sugden 1977). Therefore, the development of large, subglacial water-bodies under the Laurentide ice sheet cannot be considered unlikely, at least on the basis of thermal regime.

Shaw *et al.* (1989) drew parallels between landforms which occur extraglacially and subglacially; namely drumlinoid features that occur in a known unglaciated area and those that have been glaciated. In the subglacial case erosional residuals are interpreted as having been formed by flow separation with vortices working differentially on subglacial material. Erosion marks in bedrock appear to have formed by subglacial meltwater action (Shaw 1983, Shaw and Kvill 1984, Sharpe and Shaw 1989). Some of these marks have striking similarities, of individual forms (and group patterns), to erosion marks in turbidite beds for example. Shaw (1983) listed a variety of mechanisms that could remove material in order to create such erosion marks. These mechanisms include; solution, corrasion, fluid stressing, cavitation, and ablation. A major point made by Shaw (1983: 467) is that "although the physical and chemical mechanisms producing erosional marks are different, the forms are indistinguishable from one another". The reason for this is that "the erosional marks are dependent on separated flows" (Shaw 1983: 468).

Analogies to some of the forms described in detail, in the aforementioned literature, are also present on Mars (Mars Channel Working Group 1983) and in the Labyrinth of Wright Valley, McMurdo Sound area, Antarctica (Smith 1965, Shaw and Healy 1977), though theories concerning the formation of similar landforms are vastly different. It seems that fluvial erosional forms having generally similar characteristics occur in radically different environments, although geologic controls and varied flood magnitudes produce scale differences. From work on these seemingly disparate environments several parallel ideas are emerging. Most pertinent to the research at hand are similarities of form between residual "islands" of the "spillway" type and those of subglacial origin.

LOCATION

The study area (Figure 1-1) is located in east-central Alberta between 51°47'30" and 52°04'40" N and 111°17'30" and 111°45'30" W. This area is situated approximately

220 km southeast of Edmonton and 200 km northeast of Calgary (Figure 1-1). The study area is characterized by northwest to southeast-trending meltwater channels and is referred to, herein, as "The Coronation-Spondin Scabland" because of its unique topography and proximity to the towns of Coronation and Spondin.

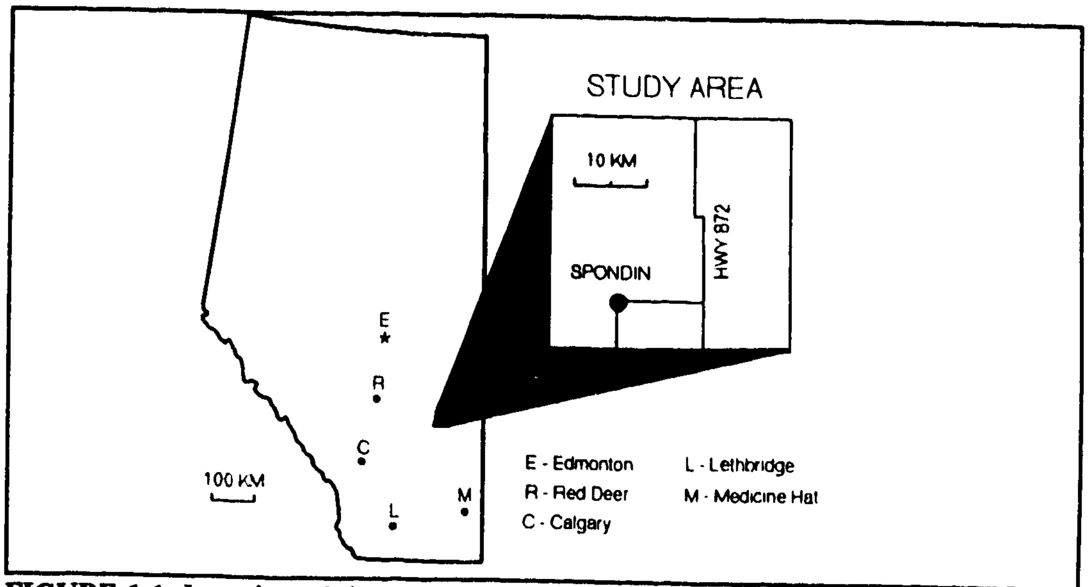


FIGURE 1-1: Location of the study area in east-central Alberta.

REGIONAL SETTING

The region is characterized by a wide array of landform assemblages. One of the most prominent zones is a north-south-trending belt of nearly flat land referred to as the "Torlea Flats" (Gravenor and Bayrock 1955, Gravenor 1956), that roughly coincide with the continuous zone mapped as draped moraine/undulating topography < 3m in Figure 1-2. Originally delineated by Warren (1937), the Torlea Flats are typically mantled by thin Quaternary sediments and display little topographic relief. In the vicinity of the study area, the Torlea Flats are approximately 80 km (50 mi) wide (Gravenor and Bayrock 1955) and cut by numerous meltwater channels. Flanking the Torlea Flats are

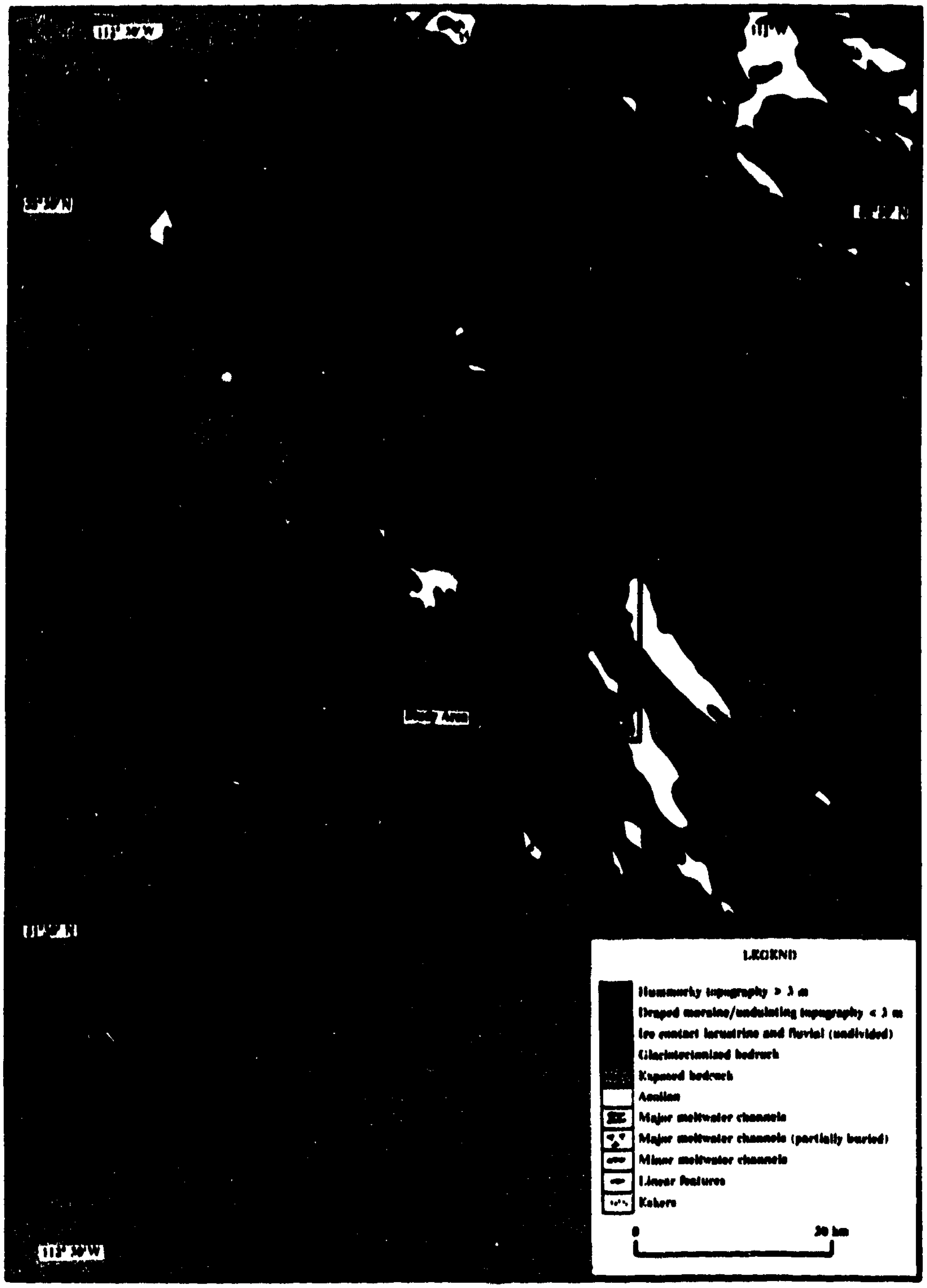


Figure 1-2: Surficial deposits and physiographic features. Modified from Shetsen (1987, 1990) and Skoye (1990).

vast expanses of hummocky topography, interspersed with glaciotectonically modified areas (Figure 1-2). These belts of hummocky terrain, including the Buffalo Lake (west of the study area) and Viking (east of the study area) moraine systems (Stalker 1960a), trend north-south, with local relief up to 20 m (Shetsen 1987, 1990). The hummocky topography is often associated with moraine plateaus and eskers (Stalker 1960b, Rains *et al.* in press). An "ice press hypothesis", applied in the Alberta context, was originally proposed by Stalker (1960b) to explain some of these forms but he had difficulty explaining the cavity-forming mechanism(s). Recently, subglacial sheetfloods have been proposed by Shaw (1988a) to explain cavity formation. Occurring in conjunction with hummocky topography are numerous zones of high relief composed partially of bedrock.

Some of the most visually striking examples of glaciotectonism in the region are the northwest to southeast-trending Neutral Hills (located northeast of the study area in Figure 1-2), composed of imbricate slabs of bedrock and till (Kupsch 1962). Other glaciotectonized zones are found in the Drumheller, Marion Lake and Buffalo Lake regions (Shetsen 1987, 1990). Interestingly, except for two isolated cases north and south of the Battle River, glaciotectonically affected zones (mapped by Shetsen 1987, 1990) are limited to areas adjacent to thinly draped Quaternary sediments (Figure 1-2).

Streamlined forms, found throughout the region, have been mapped by Shetsen (1987, 1990) and Skoye (1990). Shetsen (1987, 1990) delineated scattered occurrences of giant flutings and drumlins, whereas Skoye (1990) identified a suite of low-amplitude, subparallel flutings, discernible in the field only as minor undulations of the landscape. Long-axial orientations of these streamlined forms have important implications if they indicate direction of ice movement. If this assumption is universally correct the chaotic pattern portrayed in Figure 1-2 may conjure images of multiple episodes of ice deflection and/or readvance.

Found in association with these streamlined forms are numerous assemblages of meltwater channels, occasionally mantled by glacigenic material. These channels typically trend northwest to southeast (Shetsen 1987, 1990), approximately normal to the regional slope that declines northeastward. In addition, distinct channel networks are clustered along the eastern margin of the north-south-trending zone of thin surficial material (Shetsen 1987, 1990). Channels crossing this margin have been interpreted as being formed in crevasses along the ice margin. This may explain their intricate interlocking pattern and debris mantle (Gravenor and Bayrock, 1956). Thick Quaternary sediments are associated with mantled channel systems, whereas non-mantled channel systems are found with thin Quaternary sediments (Shetsen 1987, 1990).

Solonetzic soils, predominant in the region (Figure 1-3), coincide with the region of thin, draped moraine (Figure 1-2). The extent of solonetzic soil is partly controlled by the ability of salts to move, via groundwater, to the soil and subsoil. Thus, thin Quaternary deposits over bedrock promote solonetzic soil development by making salts available from the underlying bedrock. A distinct pattern of channel assemblages, soil zones, and surficial deposits has thus emerged. This spatial relationship is obvious, but responsible processes are not as apparent.

The study area constitutes a small portion of the Torlea Flats dominated by northwest-southeast-trending contributary and distributary channel segments, described by Gravenor (1956) as having a braided pattern. Gravenor and Bayrock (1955) postulated that subaerial spillway waters removed surficial depos ving islands of till and bedrock, but Gravenor (1956) considered it is unlikely that all of this spillway network carried water at one time. These channels, included in a deglaciation

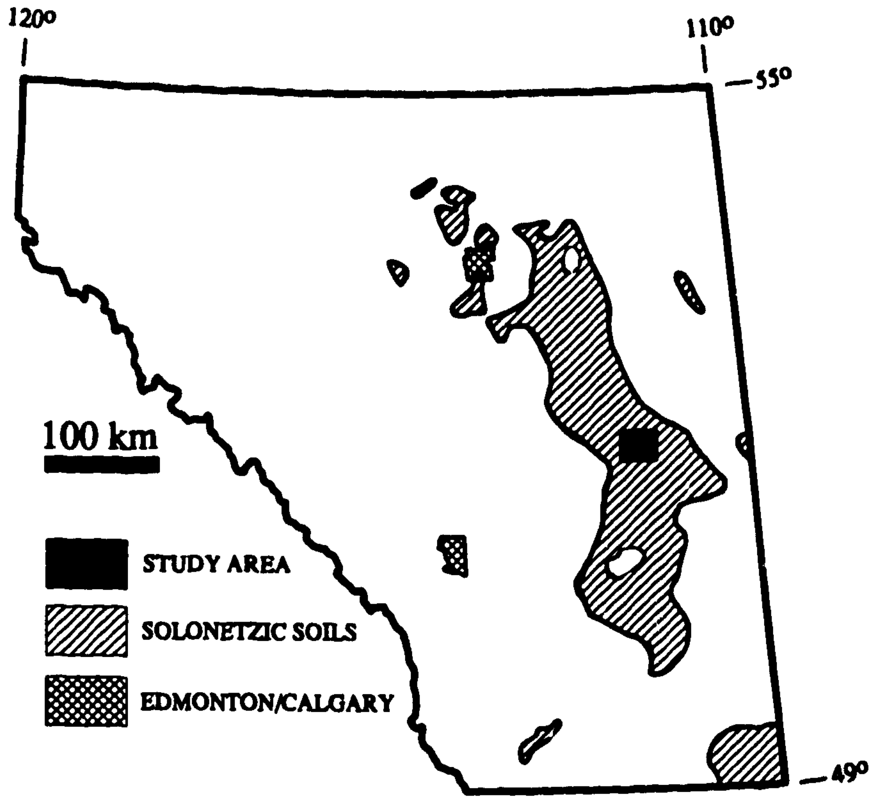


Figure 1-3: Solonetzic soil zones in southern Alberta. Modified from Odynsky (1962).

chronology by Christiansen (1979), have been mapped by Shetsen (1987, 1990) as "minor meltwater channels", but their scale is nevertheless very impressive.

BEDROCK GEOLOGY

Bedrock in the study area consists of two main sedimentary rock formations, the Upper Cretaceous, Bearpaw and Horseshoe Canyon Formations (Figure 1-4). These dip gently to the west against the regional slope; thus, the beds form "wedges" that pinch out to the east, exposing successively older beds. Studies of the Horseshoe Canyon Formation, as well as the other members of the Edmonton Group, have been prompted by occurrences of coal resources (Hughes 1984) and dinosaurian fauna (Braman and Eberth 1988). For these reasons alone, recognition of the transition between the Bearpaw and Horseshoe Canyon Formations is important. These formations were deposited during the Late Campanian to Early Maastrichtian stages of the Upper Cretaceous (Shepheard and Hills 1970). During this time, regression of the Bearpaw Sea, coupled with increased sediment input from orogenic uplift, provided the transitional sedimentary environments responsible for the character of bedrock exposed in the study area.

The Bearpaw Formation rocks derive from marine sediments deposited in an ancient sea that extended as far north as the present Athabasca River during the Upper Cretaceous (Shepheard and Hills 1970). They consist of dark grey to brownish grey marine shale and fine to medium-grained sandstone, containing occasional clay ironstone concretions (Maslowski-Schutze *et al.* 1986). This formation is attributed to prodeltaic deposition grading up into dominantly sandy topsets, indicating marine regression (Shepheard and Hills 1970). The Bearpaw Formation gradually thins to the north,

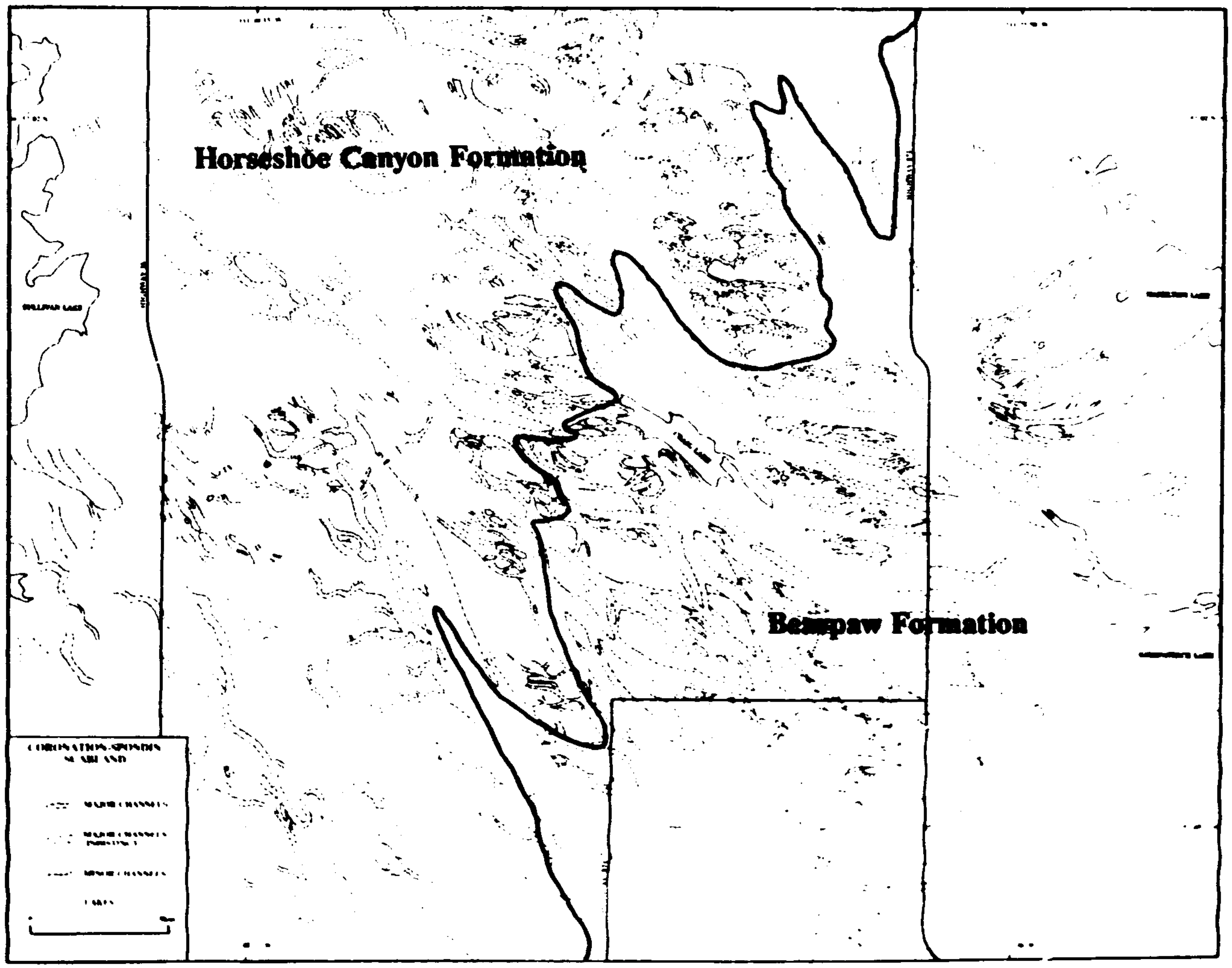


Figure 1-4: Bedrock geology of the study area.
Modified from Warren and Hume (1939) and Irish (1967).
Basemap compiled from 1:31680 air photos (see Appendix 2).

northwest, and west where it is succeeded (both laterally and vertically) by the Horseshoe Canyon Formation (Maslowski-Schutze *et al.* 1986).

The Horseshoe Canyon Formation consists of interbedded silty sandstones, siltstones, claystones, carbonaceous shales, coal, diagenetic ironstones and altered volcanic ashes (Braman and Eberth 1988). The poorly-lithified sandstones and shales represent deltaic and fluvial environments (Maslowski-Schutze *et al.* 1986). Braman and Eberth (1988) recognize four discrete facies associations; 1) tide-dominated estuarine/coastal-margin, 2) delta plain to alluvial plain, 3) Drumheller marine tongue, and 4) alluvial plain environments. The spatial variation of these associations reflects the dynamics of prograding coastal-margins interrupted by several marine transgressions (Braman and Eberth 1988). The transition between Bearpaw and Horseshoe Canyon Formations is shown in Figure 1-4. Exposures of bedrock are evident in numerous roadcuts and dugouts throughout the study area. Where bedrock is exposed, the paucity of surficial deposits is immediately apparent.

SURFICIAL DEPOSITS

Surficial deposits are limited throughout the study area but when present they mantle underlying bedrock as a thin veneer (Figure 1-2). Shetsen (1987, 1990) mapped much of the area as "draped moraine", interspersed with glaciofluvial and glaciolacustrine deposits and more limited occurrences of aeolian sands. The juxtaposition of exposed bedrock and surficial deposits attests to the generally thin cover of surficial material. Ground moraine (draped moraine of Shetsen 1987, 1990) found in the area consists of brown to grey, compact, clayey till with some stratified materials (Gravenor 1956). In addition, the till commonly contains coal fragments and montmorillonite derived from the underlying Cretaceous bedrock. This draped moraine may be up to 5 m thick (Shetsen 1987, 1990) and have inset glaciofluvial deposits.

Other glacigenic deposits include glaciofluvial and glaciolacustrine sediments. The former range from sand, mantling till or bedrock, to deposits up to 4.5 m (15 ft.) thick, containing boulders up to 0.5 m (1.5 ft.) in diameter (Gravenor 1956). Gravenor (1956) describes thick sequences of "spillway" deposits as being moderately well sorted and typically associated with till islands. Glaciolacustrine deposits are characterized by crudely stratified sands, silts and clays overlying till (Gravenor and Bayrock 1955).

CHAPTER TWO: LITERATURE REVIEW

INTRODUCTION

Similar landforms can be produced by different processes. The principle of equifinality indicates that it is not always possible to deduce a landform's origin on the basis of its morphological attributes (Selby 1982). However, the addition of sedimentological information may facilitate interpretation. Recent research concerning glacigenic landforms has provided numerous observations that appear not to be consistent with traditional theory. This chapter presents existing theory concerning paleoflood geomorphology, and characteristics of landforms that may assist in the genetic interpretation of the study area.

Flow Dynamics

Water flows of outburst floods are turbulent (Lord and Kehew 1987, Costa 1988). "Turbulence can be loosely defined as an irregular or random or statistical component of motion that under certain conditions becomes superimposed on the mean or overall motion of a fluid when that fluid flows past a solid surface or past an adjacent stream of the same fluid with different velocity" (Middleton and Southard 1984: 51). A flow is said to be turbulent when the Reynolds number (defined as the inertial force per unit area/viscous force per unit area) exceeds 500-2000 (for flows through smooth open channels) (Allen 1968). Erosional and depositional features produced by floods are expected to be dependent on the varied nature of turbulence.

Imbedded secondary flows in the primary flows are called turbulent eddies.

These are in a constant state of growth and decay (Middleton and Southard 1984). Baker (1978a) states that when the scale of turbulent eddies corresponds with the flow scale it is called "macroturbulence". Small eddies that borrow energy from larger ones make up "microturbulence" and are independent of flow scale, but dependent on Reynolds number. A continuum, ranging from macroturbulence to microturbulence, exists until there is no longer enough energy for further division (Baker 1978a) This concept is summarized in a rhyme by Richardson (1920, cited in Baker 1978a):

Big whorls have little whorls,
Which feed on their velocity:
Little whorls have smaller whorls
And so on unto viscosity.

Baker (1979) describes three main types of macroturbulence. The first is called a "kolk" and is defined as a transient eddy possessing a near-vertical axis. Matthes (1947, cited in Baker 1979) envisioned kolks as sites of intense upwards energy dissipation. The second is called a "roller", defined as recirculation downflow of a step at a right angle to the flow. Downflow of the separation point a transverse, tubular flow, isolated from the main flow, is created (Allen 1971). These are said to be separated from the external flow field. Flow separation occurs when the boundary diverges from the average direction of the flow (Middleton and Southard 1984). Erosion is concentrated where the flow reattaches to the bed (Allen 1971) and this reattachment is dependent on the Reynolds number and the ratio of flow thickness to step height (Baker 1979). The third type of macroturbulence is the "vortex" which, unlike rollers, is not separated from the external flow field but is fed by it (Baker 1979).

The sense of rotation inherent in these secondary flows is called vorticity (Middleton and Southard 1984). Vorticity is responsible for concentrating erosion at particular parts of the flow boundary. Baker (1979) stated that the tangential velocity at a point in the fluid is inversely proportional to the distance from the vortex centre. Therefore, a small vortex has a higher tangential velocity and greater erosional potential than a large vortex with the same period (i.e. erosional potential of a vortex can not be assumed solely on the basis of its radius). Vorticity in floods is initiated when channels are incapable of dissipating energy by roughness, interference, or sediment transport adjustments (Baker 1988). Conditions that are required to produce vorticity include; a steep energy gradient, low sediment transport compared to potential sediment transport, and an irregular boundary layer capable of producing flow separation (Baker 1988). Einstein and Li (1958, cited in Baker 1978a) have shown theoretically that transverse instability, resulting in longitudinal vortices, can be spontaneous. This spontaneous instability can occur in the absence of flow separation. The expected longitudinal instability is complicated in the presence of bed irregularities that cause flow separation. Bedforms related to the concentration of erosion by these vortices are expected to mimic the hydraulic attributes of the responsible fluid (Baker 1979). Large-scale vortex action is thought to be the most important manifestation of macroturbulence (Baker 1988).

In keeping with the principle of equifinality, Shaw (1983) stated that similar erosion marks can result from removal of material by solution, corrasion, fluid stressing of weak materials, cavitation and ablation. Though these mechanisms are fundamentally different, similar erosional forms may develop; this similarity is based on the premise that mechanisms operate in conjunction with separated flows (Shaw 1983). It is upon this similarity of form, resulting from a continuum of superimposed turbulent flow structures, that inference of process is undertaken (Baker 1979, Shaw 1983, Shaw and Kvill 1984, Shaw *et al.* 1989).

Streamlining

Streamlining is the process where the resistance to flow, created by an object, is reduced to a minimum (Baker 1979). The resistance to flow created by an object consists of pressure drag (form resistance), shear drag (skin resistance) and wave drag (Baker 1979). Pressure drag arises from flow separation, and energy dissipation, in a turbulent wake to the lee of an obstacle. It is highly dependent on the shape of the obstacle (Komar 1983). This component is proportional to the cross-sectional area of the obstacle, measured perpendicular to flow direction (Baker 1979). Shear drag is the tangential resistance to flow provided by the surface area of an obstacle (Komar 1983). Flow resistance is introduced by waves in a free fluid surface (Baker 1979). This component can be ignored if the obstacle is totally immersed in the fluid (Baker 1979, Komar 1983). Thus, minimization of total flow resistance is related to the interdependence of pressure and shear drag.

Many equations have been used to describe streamlined forms (Baker 1979). A simple two-dimensional form, called a lemniscate loop, is commonly used (Chorley *et al.* 1957, Baker 1978b, Baker 1979, Baker and Kochel 1979, Komar 1983, Komar 1984, Kehew and Lord 1986). A lemniscate loop is a geometric form with an algebraic equation containing a parameter (k) that governs its length and width dimensions (Komar 1984). The value of k is related to the degree of elongation of the lemniscate (k = 1 for a circle) which is approximated by the length/width ratio (Komar 1984). Baker (1978b) uses the L/W ratio as an index of elongation. Under normal flow conditions, minimum total drag is achieved by a form with a L/W ratio between 3 and 4 (Kehew and Lord 1986). Another aspect of a lemniscate loop, important for shape analysis, is the position of maximum width compared to overall form length, given by x_m/L (Komar

1984, Kehew and Lord 1986). Kehew and Lord (1986) note that the L/W ratio is established early in the streamlining process and is independent of flow duration. However, it is not until the x_m/L ratio is established that the form attains a lemniscate shape.

The hydraulic significance of the lemniscate form is that it will approximate the equilibrium form where the combination of pressure and shear drag is minimized. Since pressure drag is dependent on flow separation, a lower L/W ratio will create a greater resistance. Conversely, a high L/W ratio results in a high shear resistance. The elongation ratio, and the shape of the lemniscate, are dependent on the hydraulic nature of the fluid. Analysis has shown that the critical L/W ratio (minimum drag) depends on the Reynolds number (Komar 1983). Therefore, a flow with a higher velocity (higher Reynolds number) will be associated with a relatively elongated form (Baker 1979).

Komar (1983) also took into account the third dimension in his analysis. He found that the streamlining process was optimized when water was just deep enough to submerge the form, creating supercritical flow, increasing erosion because of increased fluid velocity. In addition, he noted that streamlining could be erosional or depositional, depending on Reynolds number.

CATASTROPHIC DRAINAGE OF PROGLACIAL LAKES

Late Wisconsinan Laurentide deglaciation resulted in the formation of proglacial lakes and spillways along ice-frontal positions. The ice sheet largely flowed up a regional slope , within Alberta, causing meltwater to be ponded between topogaphic highs to the southwest and the ice margin to the northeast, producing extensive areas of glaciolacustrine deposits. The distribution of these deposits has been used to reconstruct former ice margins and to develop chronologies of lake/spillway utilization (St. Onge 1972, Christiansen 1979, Clayton 1983, Teller 1987). The persistence of lakes was determined by elevations of lake margins, relative to land and ice barriers, water inputs from proglacial lakes further upslope, and other factors. Massive, "instantaneous" inputs of water, flowing between proglacial lakes, would have triggered drainage of the receiving basin by raising lake levels above low points on the lake margins or by breaching ice dams.

Outbursts from Glacial Lakes Missoula and Columbia produced large tracts of scabland topography, in Washington State, U.S.A., characterized by streamlined erosional residuals and deeply-incised channels (Bretz 1969, Baker 1978b, Baker and Bunker 1985). Multiple flooding episodes have been hypothesized (Waitt 1980) and were undoubtedly responsible for the degree of development of scabland tracts. Similarly, on the northern Great Plains, lakes dammed by topography and a retreating Laurentide ice sheet, episodically drained, producing spectacular meltwater channels (Kehew 1982, Kehew and Clayton 1983, Kehew and Lord 1989). Since glacial retreat occurred down the regional slope, channels were quickly abandoned for those at lower elevations. Catastrophic flooding in glaciated and nonglaciated areas has provided morphological and sedimentological evidence on which paleohydraulic reconstructions are based.

Lakes drained catastrophically in directions dictated by topographic gradient, ice-margin locations and preexisting channels (Kehew and Lord 1986). Water flows associated with outbursts would, initially, have been sediment-poor and highly erosive (Kehew and Lord 1986). Morphological and sedimentological characteristics of spillways depend on flow dynamics and the physical nature of the area inundated.

Factors Controlling Channel Morphology

Rivers entrain, transport and deposit sediment depending on water velocity, depth, slope and the amount of energy absorbed by flow resistance from bed configuration, particle sizes and sediment concentration (Ritter 1986). Episodic, catastrophic, lake drainage has resulted in channel morphology indicative of non-equilibrium conditions that existed upon flood termination (Baker 1988). The interaction of several factors will determine the final form of channels.

Bedrock characteristics and degree of consolidation affect spillway morphology. Teller and Thorleifson (1983) observed that channels cut into granitic rock, in N.W. Ontario, have limited relief (20 m) whereas prairie spillways are typically deeply incised into sedimentary rocks (Kehew 1982). Explanation of this discrepancy is related to the mechanically weak Mesozoic and Cenozoic formations that underlie many prairie spillways. These rocks were easily incised when lakes drained (Kehew and Lord 1989). Teller and Thorleifson (1983) observed that channels incised into granitic rocks have low relief (20 m) and gently sloping walls, whereas, channels cut into diabase form steep-walled canyons, 50 m to more than 100 m deep. This variation of channel morphology was attributed to enhanced erodibility along joints in the diabase (Teller and Thorleifson 1983). Similarly, Baker (1978a) attributed enhanced erosion of basalt on the Columbia Plateau, U.S.A., to joints in the bedrock, while Bretz (1969) invoked weakened bedrock for the initiation and proliferation of intrachannel cataracts. Baker (1988) noted that plucking, most efficient in jointed bedrock, resulted in channels with low width/depth ratios and high sinuosity.

In addition to bedrock character, composition of surficial sediment is an important factor in the determination of channel morphology (Kehew and Lord 1986, Baker 1988). Bank materials with high silt-clay contents tend to result in narrow, deeply incised channels while coarser-grained bank sediments result in wide, shallow channels (Kehew and Lord 1986). Sediment type is correlated with sinuosity and width/depth ratios of the channels (Kehew and Lord 1986).

These controls are insignificant if floodwater encounters preexisting channels. Kehew and Clayton (1983) state that floodwater encountering preexisting channel incises; whereas, if a preexisting channel was not present, a scabland-like area would be formed first, followed by incision. Kehew (1982) concluded that an absence of a scabland-like area indicated that floodwater never reached bankfull. The absence of a scoured outer zone or inner channel may indicate preexisting channels were reutilized, or that outbursts encountered unchannelized terrain.

Waitt (1980) proposed approximately 40 flooding episodes for Glacial Lake Missoula, U.S.A., and Bretz (1969) noted the importance of recurring floods in the headward retreat of scabland cataracts. Teller and Thorleifson (1983) postulated that some northern Great Plains channels may predate the last glacial retreat, based on till draping of channels. It appears that the morphology of channels is partly dependent on whether flood water entered existing channels. For this reason the possibility of multiple flooding must be considered.

Channel Morphology

Catastrophic lake outbursts produced a plethora of channels and depositional forms. Spillways are identified on the basis of discrete cutbanks, consistent bank heights, relatively uniform widths and regular meander shapes (Clayton *et al.* 1980, cited in Kehew and Clayton 1983). Spillways of the northern Great Plains consist of two types; broad and shallow, or narrow and deep (Kehew and Clayton 1983). These types may be part of a continuum of forms representing an evolutionary sequence (Baker 1988). If this is the case, flood duration can be inferred from the relative "maturity" of the inner and outer channels. Incision of inner channels occasionally resulted in abandonment of the outer surface, giving them a terraced form. Outer zones, according to Kehew and Lord (1986, 1989), are characterized by two transitional types; slightly-scoured areas where anastomosing channels predominate, and deeply-scoured areas where longitudinal grooves and boulder lags predominate. Erosional residuals, approaching lemniscate shapes, are found between anastomosing channels in slightly scoured areas and are isolated in deeply-scoured areas (Kehew and Lord 1986). The shapes of residuals in the outer zones are variable where flow was brief but, given longer periods, streamlining resulted in more uniform residuals. Inner zones consist of deep, narrow channels. These channels may bifurcate and rejoin, leaving intrachannel residuals. The formation of inner channels appears to be a manifestation of coalescent, longitudinal vortices (Kehew and Lord 1986).

Spillway morphologies in the northern Great Plains suggest that high-velocity flows inundated the landscape, carving broad, shallow, anastomosing channels. As flow persisted, longitudinal vorticity produced longitudinal scours, and coalescence of longitudinal vortices incised an inner channel. This channel may have conveyed all the available water in later stages of the flood. Such an evolutionary sequence has been simulated in flume experiments by Shepherd and Schumm (1977).

Scabland topography, found in slightly-scoured areas of outer spillway zones (Kehew and Lord 1989), and in zones of spillway avulsion (Kehew 1982), is characterized by anastomosing channel patterns that relate to the inability of preflood channels (or valleys) to convey all floodwaters (Baker 1978b). According to Baker (1978b), channel anastomosis occurs at three different scales; (1) regional scale dictated by preflood topography, (2) individual channel scale, controlled by geologic structures, and (3) small-scale, associated with minor divide crossings. Associated with these anastomosing channels are numerous erosional and depositional bedforms that have a similar hierarchical nature. Baker (1978b) recognises two major scales of forms, macroforms and mesoforms. Macroforms are scaled to channel width while mesoforms are scaled to flow depth. Jackson (1977, cited in Baker 1978b) also includes microforms but, since these forms are preserved only in slackwater deposits, they are of lesser importance in a discussion of large-scale morphology.

Striking features of the channeled scabland in Washington State, U.S.A., are residual hills composed of bedrock and loess. Baker (1978b) observed that a hierarchy of residual hills exists. Residuals that have a quadrilateral shape are separated by narrow channels. Various amounts of dissection of these large residual hills have resulted in a wide range of residual forms and sizes. Patton and Baker (1978) describe small residuals as having sharp upstream prows, steep faceted flanks, and long tapering tails. The form similarity with some types of drumlins has been noted (Baker 1973; Shaw *et al.* 1989). Whether or not these residuals were submerged in the formative flow has important implications for the gross residual form, as well as the type and position of associated gravel bars (Patton and Baker 1978). Loess residuals that were completely submerged have, in proximal areas, a thin veneer of gravel which thickens distally. Partially-submerged residuals are typified by large-scale cross-bedding and thick deposits in re-entrant channels. Residuals that were not submerged have generally steep, flanking scarps that truncate preflood drainage. The gross shape shows striking similarity to bars in braided rivers.

Residuals completely submerged by floodwater show signs of substantial streamlining (Baker 1978a, Patton and Baker 1978). Streamlining is produced by shaping an obstacle to reduce flow separation along a fluid boundary (Baker 1978b). Baker (1978b) states that subfluvially-formed streamlined forms may exhibit flow obstacles that localized the resistant landform, crescent-like scour marks, downstream-tapering streamlines on the adjacent channel floor, and oblique channels cutting through small divides at the crest. Scour marks along the lateral and proximal margins of residuals have been attributed to vortices in the flow (Baker 1978a).

Sediment Characteristics

Deposits associated with catastrophic releases of glacially-derived meltwater can be divided into those scaled to flow width and those to the flow depth. Some deposits scaled to flow width include longitudinal bars (Patton and Baker 1978, Lord and Kehew 1987), expansion bars (Patton and Baker 1978), eddy bars (Baker 1978b) and slackwater deposits (Bretz 1969, Waitt 1980, Atwater 1983, Waitt 1983). Because of the erosive capacity of outburst floods, sedimentological evidence of a previous episode is usually destroyed by the next event. Channel deposits are of limited use when reconstructing sequence of events. Deposits associated with backflooding up tributary valleys, however, have provided evidence for multiple flooding events (Baker and Bunker 1985).

Deposits related to backflooding in the channeled scabland of Washington State, U.S.A., tend to have a rhythmic nature, similar to subdivisions b-e of an ideal Bouma sequence (Waitt 1980). This rhythmicity expresses itself as a transition from plane-bedded medium sand, to ripple-drift-laminated fine sand, to plane-laminated very fine sand, to plane-laminated to massive silt (Waitt 1980). This transition represents decreasing current velocities, with an increase in deposition from suspension (Waitt

1980). In addition, rhythmites tend to thin upsection (Waitt 1980, Atwater 1983) and upvalley (Baker and Bunker 1985). The presence of large boulders of exotic lithologies is explained by ice rafting (Waitt 1980). Also, the grain size in the beds fines upvalley (Baker and Bunker 1985). Flow direction indicators, such as foresets, are typically oriented upvalley (Bretz 1969), but reversed currents have been noted (Waitt 1980).

Bretz (1969) maintains that the character of these rhythmic sequences indicates turbulent surges within floods. Waitt (1980, 1983) believes that each rhythmite represents a separate flood. He cites the absence of injection and loading structures, presence of shallow-water fauna, apparent reworking of aeolian sand (rip-up clasts of sediment deposited subaerially), presence of uncontaminated tephra, rodent burrows, and vertebrate bones, as evidence of multiple flooding events. This evidence led Waitt (1980) to believe that at least 40 Lake Missoula floods occurred, whereas, similar records in the Sanpoil Arm of Glacial Lake Columbia led Atwater (1983) to conclude that there were at least 71 floods from Lake Missoula. Part of this apparent discrepancy may relate to multi-peaked flood hydrographs. Baker and Bunker (1985) alluded to the importance of complex flood routing in multi-peaked hydrographs.

Longitudinal bars, unlike slackwater deposits, indicate high-velocity flows with a high capacity for sediment transport. One of the most common forms is the pendant bar (Baker 1978b, Patton and Baker 1978, Baker and Bunker 1985, Lord and Kehew 1987). These bars are associated with flow separation that occurs downstream of obstacles (Baker 1978b, Patton and Baker 1978). In the channeled scabland, Washington State, U.S.A., this occurs in the lee of bedrock steps or erosional residuals (Patton and Baker 1978). Flow separation is fundamentally important in the formation of these bars because a flow capable of moving large boulders is not expected to deposit much smaller fractions (Baker 1978b). Typically, these bars are streamlined (Baker 1978b) to minimize the resistance (Komar 1983). This partially relates to the prevention of flow separation. The bars are usually most abundant on channel margins (Patton and Baker 1978).

Internally, related deposits may take on a wide range of characteristics. Pendant bars associated with Lake Missoula floods are up to tens of metres thick (Baker 1978b), and exhibit avalanche-face accretion (Baker 1978b, Patton and Baker 1978). Baker (1978b) describes these bars as having well sorted, subrounded, boulders and cobbles in an open-work structure. Lord and Kehew (1987) noted pendant bars that are massive, and interpreted them as being deposited in hyperconcentrated flows.

Point bars associated with large flood events have also been noted. Atwater (1987) described bouldery gravel in the form of a point bar that was probably shaped by a flood(s). Point bars in spillways on the Great Plains consist of massive, matrix-supported, very poorly-sorted, cobble gravel, commonly containing boulders (Kehew and Lord 1987), or large boulders in a matrix of sand and fine gravel (Kehew and Clayton 1983). In addition, Kehew (1982) noted a large point bar, on the inside of a meander bend, which has an upper sequence of moderately well sorted, cross-bedded sand and gravel overlying poorly sorted, non-bedded gravel with large boulders. Kehew (1982) explained some bars as being erosional, either forming as flood stage dropped or as products of multiple events.

Eddy bars formed in sheltered areas adjacent to channeled scabland channels, Washington State, U.S.A., and depict variable flow directions (Baker 1978b). These deposits generally are poorly sorted and indicate the importance of turbulent flow in their deposition (Baker 1978b). Alcove deposits, found in spillways on the Great Plains, were created when the banks of spillways failed during incision and were subsequently infilled by hyperconcentrated flows (Kehew and Lord 1987). These bars are similar in that they occur in zones of rapid flow expansion. However, eddy deposits have highly variable structure and grain size within a single deposit.

Expansion bars were deposited where flow competence declined downflow of a constriction (Patton and Baker 1978). These thin deposits were formed downstream of cataracts or where channels became unusually wide (Patton and Baker 1978). Lord and Kehew (1987) also noted gravel bar deposition in zones of flow expansion and, like other bar forms in Great Plains spillways, these were attributed to deposition from hyperconcentrated flows.

Typical forms and deposits that are scaled to flow depth include giant current ripples and boulder lags. Giant current ripples formed by catastrophic lake drainage are typical on bar surfaces (Baker 1978b, Patton and Baker 1978) and on top of residual hills. In both cases the current ripples supplied sediment for aggradation of long foresets, typical of bar deposits in the lee of obstacles (Baker 1978b, Fig 5.17). Baker (1978b) described current ripples having chords ranging from 20 to 200 m, and heights of 1 to 15 m. The lee slopes are at 18-20° whereas the stoss sides lie at 6-8°. Internally, clasts 1 to 5 m in diameter are found, while the median size is in the pebble fraction. Ripples are foreset bedded (~27°) with individual foresets being well sorted. Trough cross-stratification is rare but, where present, may represent scour fills. Boulders and cobbles provide an imbricate pavement on the stoss side of ripples and are present elsewhere in the channels.

Boulder lags exist in many channels that have been modified by catastrophic flood discharges (Kehew 1982, Kehew and Clayton 1983, Teller and Thorleifson 1983, Baker 1978b, Kehew and Lord 1989). Teller and Thorleifson (1983) and Clayton (1983) observed that rounded boulders were common on the floors of channels and tended to fine downstream. In many cases, boulders mantle bar deposits (Kehew 1982) and may be the result of winnowing of the surface (Baker 1978b).

CATASTROPHIC SUBGLACIAL FLOODING

The reality of subglacial water has been accepted for some time, but theories concerning catastrophic subglacial floods have had more limited acceptance. Observations have been mounting that add credibility to this theory, including; morphologic analogies, landform associations, sedimentologic, and isotopic evidence.

Sheetflow versus Channelized Drainage

Research on subglacial flooding has traditionally focused on channelized flows (Wright 1973) but recently the importance of sheet flows (Shaw 1983) has been established. Weertman (1972) theorized that a water film existed at the glacier-bed interface, facilitating basal sliding. Presence of a basal water film was rejected by Nye (1976) because it did not allow for regelation. Likewise, Drewry (1986) rejected the concept because bed irregularities should create pressure gradients that would cause water to become channelized. Thus, basal meltwater sheets represent unstable conditions which exist only when channels are either nonexistent or are unable to convey the flow. Under these conditions high pressures decouple the glacier from the bed and water is able to flow in the void created by this hydraulic lifting.

The transition from a sheet flow to channelized flow is related to adjustment of the ice sheet and water pressure. Shreve (1972) and Röthlisberger and Lang (1987) established that large subglacial conduits are dominant over smaller ones. This relationship is based upon pressure differences, as well as melting rates, dependent on turbulent heat transfer and the antecedent water temperature (Shreve 1972, Röthlisberger and Lang 1987).

The transition from sheet flood to more stable forms has been noted. Shaw (1983), Shaw and Kvill (1984) and Shaw and Gorrell (1991) described anastomosing channels, and cross-cutting drumlin fields, with eskers in them. Using superimposition and cross-cutting relationships Shaw (1983) and Shaw and Kvill (1984) established that drumlins were formed by sheetflows, whereas tunnel channels and eskers were subsequently formed during progressive channelization. Wright (1973) also noted this association and concluded that trenches and eskers represented successive subglacial hydrologic conditions during ice wastage.

EVIDENCE FOR SUBGLACIAL FLOODS

Morphologic Evidence Supporting Subglacial Floods

Many lines of evidence illustrate the importance of catastrophic subglacial floods during the Pleistocene. The evidence is based on numerous form analogies, and assemblage analogies, between small-scale erosional marks and large-scale subglacial landforms. Shaw (1983) was the first to note that many drumlin fields bear a striking resemblance to casts of erosional marks from turbidity currents. The analogies, apart from the obvious scale difference, extend not only to individual forms and regional variations, but also to superimposition of furrows on some drumlins (Shaw 1983). Shaw (1988b), in reference to erosional marks near Wilton Creek, Ontario, concluded that flutes were formed in a coherent field. This conclusion was based on (1) similar form and scale and (2) an absence of cross-cutting relationships. He directly opposed Dahl

(1965) who theorized that formation occurred in subglacial channels as discrete fields.

Form analogies involving small erosion marks and drumlin-scale features must be related to an erosional mechanism which is independent of absolute size. This mechanism can be engendered by turbulent flow. Allen (1971) gave a range of Reynolds numbers within which erosional marks are expected to form. Shaw (1983), Kor *et al.* (1991) and others, have implicated vorticity in the repetitive nature of erosional marks. Shaw and Kvill (1984) illustrate how erosion marks are associated with some types of drumlins.

The formation of erosional marks can be explained by the interaction between coherent flow structures and bed character (Kor *et al.* 1991). Bed irregularities may provide obstacles around which turbulent flows are diverted, producing a vertical pressure gradient which causes the flow to separate (Sharpe and Shaw 1989). This is not always the case, since some erosion marks cross-cut joints (Sharpe and Shaw 1989). The newly-formed vortex impinges nearly perpendicularly to the bed, concentrating erosion (Sharpe and Shaw 1989). This results in two oppositely-rotating vortices being diverted around the obstacle. Together, these form a horsehoe vortex (Sharpe and Shaw 1989). The erosion marks that result from horseshoe vortices have, typically, a crescentic scour around the obstacle and lateral furrows extending downflow. In the event that one lateral furrow becomes more developed than the other, a comma-form may develop (Kor *et al.* 1991).

Sharpe and Shaw (1989) suggest another way in which similar erosion marks might develop. This alternative is prompted by the fact that some lateral furrows exist without a linking crescentic scour. They envisage accentuated erosion along the flanks of an emerging obstacle, producing furrows which grow headward, eventually joining in a crescentic furrow. In cases where the erosion was interrupted, a narrow neck remained. Flow separation and the resulting vorticity related to the furrows would cause the furrows to become distally shallower and wider.

Other types of erosional marks are associated with the impingement of vortices on the bed. Kor *et al.* (1991) illustrate how varying the angle of impingement could initiate different configurations of erosional marks. Low-angle impingement could result in spindle-shaped marks, whereas, higher-angle impingement could result in muschelbruche. Muschelbruche evolved into sichelwannen if bed relief was increased to the point where flow separation was made possible, and roller vortices were initiated (Kor *et al.* 1991).

Subglacial Glaciofluvial Deposits

Less is known about sediments associated with subglacial flooding events than is known about erosional forms. This is related to the highly erosive nature of the floods. Sediments that have been studied include those associated with cavity-fill drumlins (Shaw and Kvill 1984), subglacial gravel dunes (Shaw and Gorrell 1991) and Rogen moraine (Fisher and Shaw 1992).

Sediments of cavity-fill drumlins are found to be largely water deposited and display significant resedimentation by mass movement (Shaw and Kvill 1984). They also observed that the drumlins were covered by boulders that were inset into the drumlins. Internally, cavity-fill drumlins were found to contain large amounts of sand, with interspersed boulders. Water-lain sediments, resedimentation by mass movement, the presence of striated boulders and angular clasts (indicating limited fluvial transport) may all be explained if the deposition was by flowing water, with possibly some contributions from the cavity roofs (Shaw and Kvill 1984).

Subglacial dunes were found between drumlins, and in tunnel channels, where they are associated with eskers (Shaw and Gorrell 1991). Large-scale cross-bedding was noted in dunes that were up to 10 m high. Reactivation of cross-bedding was noted on individual foresets which were found to contain bimodal, openwork and multimodal gravels. Longitudinal sorting, and flow separation, were implicated in the composition of individual foresets.

Sediments found in Rogen moraine include diamicton intercalated with sorted sediment, such as poorly sorted and stratified gravel (Fisher and Shaw 1992). Debris flows were thought to be responsible for the orientation of clasts, intercalation of silty diamicton and sorted sediment, and bedding consistent with the slope of the form. Hyperconcentrated flows were ruled out for formation of the diamictons, on the unlikelihood of clusters of clasts being preserved in a flow with high shear.

Landform Associations

Drumlins are commonly found associated with anastomosing tunnel valleys, crescentic scours, and eskers (Shaw and Kvill 1984). Tunnel channels that contain eskers are observed to truncate drumlins and are found in conjunction with incomplete drumlins. Large gravel bedforms are found between drumlins and along the floor of tunnel channels, and attest to deep, high-velocity flows during formation of these landforms (Shaw and Gorrell 1990). Large regions containing drumlins, erosion marks, tunnel channels, eskers, and gravel dunes, all with consistent flow directions, attest to broad sheet flows (Shaw and Gilbert 1990). Rains *et al.* (in press) have attempted to link flood events, in Alberta, thought to be responsible for formation of drumlins, giant flutings, hummocky terrain and broad, scoured zones.

Extraglacial Evidence for Subglacial Flooding

Cataclysmic proglacial lake drainage, in the absence of ice dams, has been noted by a number of researchers (for example, Kehew and Clayton 1983, Kehew and Lord 1986). Shaw *et al.* (1989), skeptical of proposed mechanisms for catastrophic drainage of proglacial lakes under steady-state conditions, propose initiation of drainage by sudden water inputs. They state that floodwaters, thought to be responsible for drumlin formation, could supply the sudden inflows, setting off the "domino effect" (proposed by Clayton (1983), for example), thought to have characterized proglacial lake drainage.

Flows of this magnitude would have had a profound effect on global sea level (Shaw 1989). The volume of water estimated to have formed the Livingstone Lake drumlin field (Shaw and Kvill 1984) would have caused a eustatic sea level rise of 0.23 m (Shaw 1989, Shaw *et al.* 1989). Emiliani *et al.* (1975) drew on a pronounced peak in the oxygen isotope profile as evidence for a "freshening" of Gulf of Mexico waters by Late Wisconsinan floods about 11,600 years BP. This isotopic evidence is substantiated by a microfossil-poor sediment unit that Leventer *et al.* (1982) attibuted to rapid deposition from a period of high meltwater discharge. It should be noted, however, that the Livingstone Lake "event" has recently been interpreted to have occurred between 18 and 15 ka B.P. (Rains *et al.* in press).

Probable Water Sources

Shaw *et al.* (1989) propose that flows at least 150 km wide, several tens of metres deep, and having velocities of at least 2-10 m/s would have resulted in discharges ranging from 0.6 to 6.0 x 10^7 m^3/s. This estimate appears to be consistent with estimates of other catastrophic flood events, such as 2.13 x 10^7 m^3/s for Glacial Lake Missoula floods (Baker 1971) and 4.5 x 10^6 m^3/s for tunnel valleys on the Scotian Shelf , if all channels were operating simultaneously (Boyd *et al.* 1988). Large volumes of water are expected to have been associated with glacial surging (Shaw *et al.* 1989)

One of the major arguments against catastrophic subglacial flooding concerns water sources. Wright (1973) postulated that geothermal and basal frictional melting could not produce sufficient volumes of water necessary to produce tunnel valley systems in Minnesota, U.S.A., in the event that supraglacial water could not reach the base. Oswald and Robin (1973) showed that lakes occur beneath parts of the Antarctic ice sheet, and Shoemaker (1991) showed theoretically that ponding of "mega-subglacial lakes" beneath continental glaciers is dependent on bed characteristics. Shoemaker (1992a) suggested that episodic glacier surges could be linked with subglacial flooding events and Shoemaker (1992b) provided evidence supporting catastrophic drainage from a large subglacial lake in the vicinity of Hudson Bay. However, drumlins and associated features, thought to have formed during meltwater floods, extend almost to ice sheet centres where supraglacial lakes are unlikely to be found (Shaw *et al.* 1989). Shoemaker (1992b) stated that, not only was it possible for drainage to occur toward the terminus, but drainage reversal was possible, given sufficient head differences between subglacial and proglacial lakes. In addition, Shoemaker (1992b) suggested that a low ice gradient would exist over a large subglacial lake, which might allow trapping of supraglacial meltwater, and given episodic glacier surges (Shoemaker 1992a) crevassing could provide a connection between supra and subglacial water.

CHAPTER THREE: REGIONAL SETTING

The merit of a landforms-genesis theory is determined by its ability to account for regional variability while also explaining specific landform morphologies and sediments. Applications of theory to most paleoenvironmental interpretations are tenuous because it is usually not possible to extrapolate experimental conditions to a regional scale. Theoretical inadequacies are inherent but, given current knowledge, it is possible to provide a "most probable" hypothesis which best explains the internal and regional character of the landscape.

The wide range of drumlin shapes has also been compared to erosion marks found on bedrock surfaces. These erosion marks are shown to be products of turbulent subglacial sheet floods, because of the superimposition of striations on and around the erosion marks (Shaw 1988b). In addition to the erosion marks formed in the overlying ice, and the substrate, turbulent subglacial sheet floods are implicated in the formation of erosional drumlins carved out of preexisting material (Shaw and Sharpe 1987, Shaw *et al.* 1989). To accept this theory of drumlin formation, it is necessary to evaluate it on the basis of regional landform associations.

Numerous landform elements have led to the application of this theory on a regional scale. The close association of drumlins and anastomosing tunnel valleys has been noted (for example Wright 1973). Large-scale anastomosis has been associated with extreme discharges of relatively short duration (Wright 1973, Boyd *et al.* 1988). Shaw *et al.* (1989) compared some drumlins with erosional remnants in the channeled scabland, Washington State, U.S.A., that are known to have formed proglacially. Loess hills, formed subfluvially (Baker 1978b), are identical to some drumlins, except for minor relief elements, and are associated with longitudinal grooves. Likewise, Komar (1983) suggested that the form of streamlined islands on Mars indicated the presence of a turbulent fluid wake, as opposed to laminar ice flow. Large-scale anastomosis has also been reported in association with proglacial lake outburst floods (Kehew and Lord 1986). In this setting, drumlin-shaped residuals were found in conjunction with longitudinal grooves and other forms, more traditionally attributed to fluvial processes.

Application of the subglacial flood hypothesis to large-scale drumlins, anastomosing tunnel channels, and s-forms raises questions as to its validity in the formation of other glacigenic landforms. Fisher and Shaw (1992) proposed that Rogen moraine may also be related to subglacial flooding events. Rogen moraine are suggested to have formed as features deposited in subglacial cavities, created as large sheet flows cut transverse erosion marks up into the ice (similar to those found on the underside of river ice). However, Fisher and Shaw (1992) recognised that purely erosional forms may also exist. In addition to Rogen moraine, some types of hummocky terrain have also been attributed to subglacial sheet flood erosion (Rains *et al.* in press). Hoppe (1952) and Stalker (1960b) argued earlier that many hummocks could be explained by the squeezing of subglacial material into cavities in the ice. Subglacial sheet floods provide the mechanism by which somewhat regularly-spaced cavities could be formed. Shaw (1988a) speculated that hummocky moraine may result from the pressing of till into scallop-shaped cavities eroded into the underside of the ice by flowing water. A linked formative process of hummocky terrain by subglacial flooding is largely erosional. Rains *et al.* (in press) proposed that hummocks and troughs are a product of subglacial sheet flood erosion, where mutual interference of thin sheet flows excavated material between the hummocks. This is substantiated by the observation that some hummocks are composed of contorted bedrock, the structures of which are not concordant with the surface forms of the features.

On the assumption that flutings and drumlins are subglacial, glaciofluvial landforms, Rains *et al.* (in press) reconstructed hypothetical flowlines in Alberta from features mapped earlier by Shetsen (1987, 1990) and Skoye (1990), among others. Cross-cutting relationships were used by Shaw and Gilbert (1990) to reconstruct flowlines of two flooding events in Ontario. Discrepancies in trends, and cross-cutting relationships, attest to multiple flood events in Alberta, the largest of which was the so-called Livingstone Lake "event". This "megaflood" is thought to have operated contemporaneously with discharges from mountain sources under a zone of relatively thin, coalescent, Laurentide and Cordilleran ice (Rains *et al.* 1990, Rains *et al.* in press). The Livingstone Lake "event" is thought to have originated in the Northwest Territories and, once initiated, produced flood paths that include drumlins around Lake Athabasca, the giant flutings near Athabasca town, and which was then partially diverted around and over large hummocky complexes further south, producing zones of convergent and divergent sheet flows throughout southern Alberta (see Rains *et al.* in press, Figures 1 and 2). Cross-cutting relationships observed for some fields of streamlined features indicate multiple flooding events. Flutings located near Lac La Biche, are truncated on their upstream end and are thought to have preceeded the Livingstone Lake "event".

Southern Alberta is largely mantled by varying thicknesses of glacigenic material (Shetsen 1987, 1990). Regions having only a thin drape of glacigenic material are associated with solonetzic soils (Odynsky 1962, Rains *et al.* in press). These soils are formed when salts from the underlying, partly marine, sandstones and shales are brought to the surface by evaporative processes. One main path of the Livingstone Lake "event" sheet flow coincides with major, Alberta, solonetzic soil zones. Within these soil zones large areas of undulating topography are interrupted by several channel networks (Shetsen 1987, 1990). Some of these networks are linked to esker systems that are especially striking along the eastern margin of the solonetzic zones, where mantling of channels by thicker glacigenic material is also known. Some channels have paleoflow directions not consistent with Livingstone Lake "event" paleoflows. One of these channel assemblages, located in the centre of the eastern flood path, is an anastomosed complex incised primarily into bedrock. This is called the Coronation-Spondin channeled scabland. It is within a broad zone of scoured bedrock, and is observed to cross-cut giant flutings mapped by Skoye (1990), indicating that it postdates removal of surficial sediment by the Livingstone Lake "event" (responsible for the fluting formation). The Coronation-Spondin scabland tract is characterized by various scales of anastomosing channels separated by broad, shallow channels that display limited sinuosity. The degree of anastomosis and orientations of channels are highly variable. A regional view (Figure 3-1) displays the anastomosing tracts and their association with hummocky topography to the southwest, glaciotectonized zones to the northeast and broad, undulating, scoured zones to the northwest and south.

The flexibility of a theory invoking large subglacial "megafloods" has made it possible to link together the formation of hummocky moraine, Rogen moraine, tunnel valleys, drumlins, giant flutings, and erosion marks on bedrock. The ability to integrate several landform elements into a coherent genetic environment has made it appealing. The following three chapters detail morphologic and sedimentologic observations that support a subglacial origin for the Coronation-Spondin scabland.

Figure 3-1: Regional setting: The Coronation-Spondin Scabland and locations of Sullivan Lake (a), subtle, subparallel, giant flutings (b), hummocky terrain (c) and horseshoe shaped scour (arrows). Modified LANDSAT MSS subscene (Appendix 2).

CHAPTER FOUR: CHANNEL FORMS

CHANNEL CLASSIFICATION, ORIENTATION AND PATTERN

Channel Classification

The Coronation-Spondin scabland is an integrated channel network composed of channels that display a range of sizes and forms. Smaller channels are typically narrow and deep, whereas larger channels are broad and shallow. Channel size ranges from small-scale channels superimposed on depositional bars to large-scale forms that demarcate distinct zones of channelization.

A threefold classification can be based on channel size and morphology. Large-scale channels include those that are broad and shallow, up to 5 km wide and seldom exceeding 20 m in depth. Two large-scale channels occur in the study area, curving in arcuate paths from the northwest to southeast (Figure 4-1). These are broadly scoured, with erosional and depositional bedforms reflecting convergent and/or divergent flow patterns superimposed on the general, southeastward, primary flow. Large-scale channels have abrupt origins where many smaller channel segments converge. The large channels are up to 20 km in length, though subtle channel expression in places makes precise lengths difficult to ascertain. This category includes those easily recognized as single channel segments, having contributary channel junctions, but not truncated by larger channels. They have low degrees of sinuosity and end where bifurcation marks a transition to anastomosing systems, or alternatively (as in the case of the eastern channel), in an amorphous non-channeled zone. Smaller channels that form contributary and distributary linkages with large-scale channels comprise the intermediate-scale

Figure 4-1: The Coronation-Spondin scabland is dominated by two broad, shallow large-scale channels that trend northwest to southeast (a). Smaller channels display variable orientation and dissection of the landscape. Modified LANDSAT MSS subscene (Appendix 2).

channels.

Intermediate-scale channels are defined as anabranch segments constituting highly variable channel networks. These channel segments dissect zones demarcated by the large-scale channels, in anastomosing to linear patterns (Figures 4-1 and 4-2). Intermediate-scale channels are continuous in these zones, forming contributary and distributary junctions with large-scale channels. These channels are typically narrow and may be comparable in depth to the large-scale channels. Individual anabranches are slightly sinuous to straight, with highly variable gradients that often display concave-up and/or convex-up long profiles (Figure 4-7). The dissection of the zones between large-scale channels is variable. Intermediate-scale channels responsible for well developed dissection are relatively large and have distinct networks. Alternatively, those zones that are poorly dissected display chaotic channel networks and small, poorly defined, channel segments. An integrated channel network illustrating distinguishable junctions, with similar-sized channels, differentiates intermediate-scale channels from small-scale channels.

Small-scale channels are defined as channel forms superimposed on the residuals that are demarcated by intermediate-scale channels (Figure 4-2). These channels are expressed as discontinuous, straight to slightly sinuous channel segments. Small-scale channel discontinuity is shown by segments that may originate in the residual flanking channels or on top of residuals. These channel segments are indistinct in some areas and well defined in others (indicated by channels that appear disconnected from the networks in Figure 4-2). Small-scale channels may have well defined junctions with intermediate-scale channels, becoming less distinct as they cross residuals. These channels may be either shallow, nearly indistinct segments, or narrow and well defined

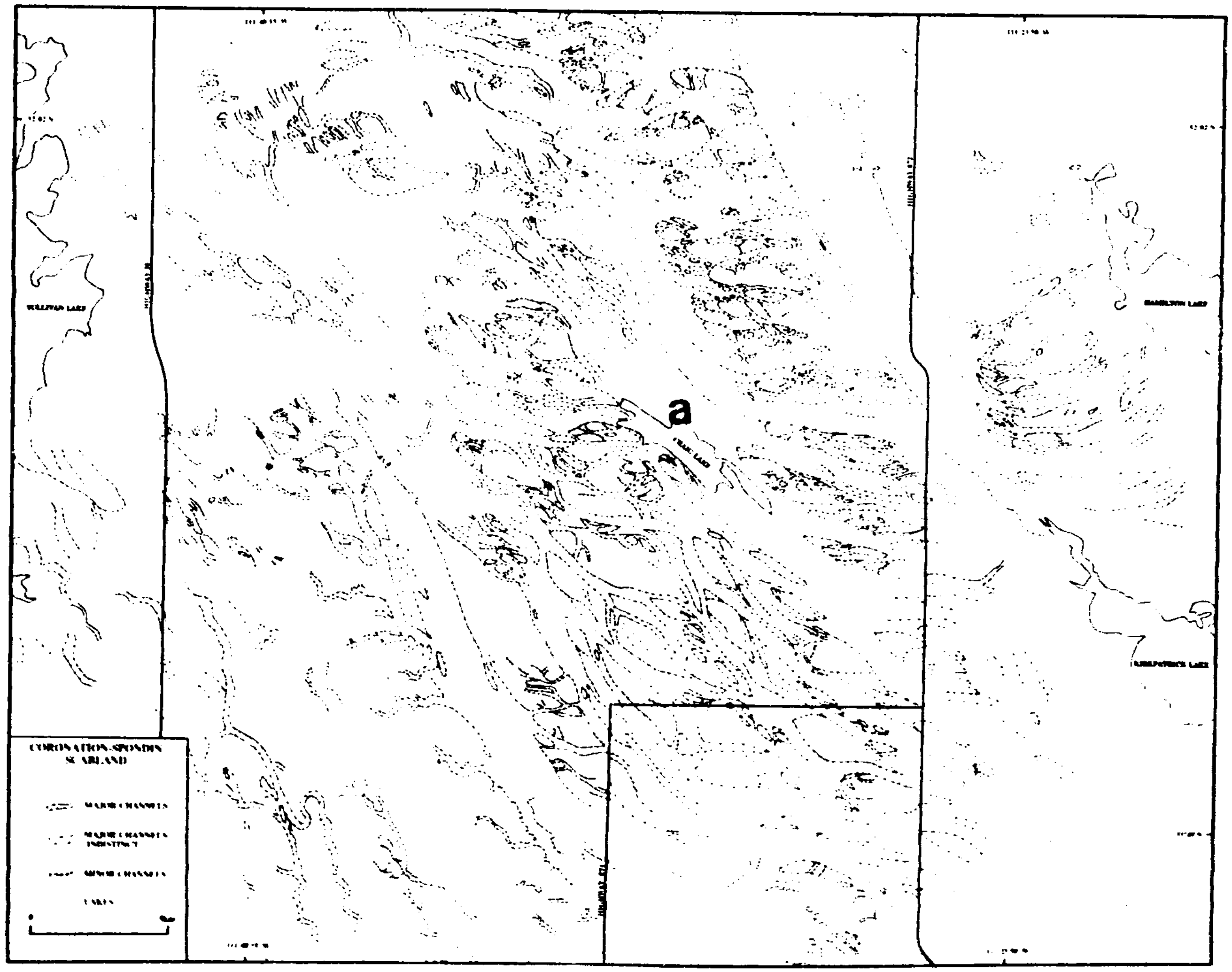


Figure 4-2: The Coronation-Spondin scabland. An intricate, hierarchical channel network characterized by numerous contributary and distributary junctions. Compiled from 1:31680 air photos (Appendix 2).

systems. These channels, and their association with larger forms, constitute an integrated system ranging from small channels (metres in size) to large-scale channels in the order of kilometres across. Many small-scale channels are distinguished from individual scours on the basis of their interconnectivity and sinuosity. Small-scale channels may be expressed as incomplete anastomosing channel networks that lack links with other recognizable channels. Where small-scale channels are indistinct, residuals lack recognizable superimposed forms.

A continuum of interconnected channels, ranging widely in size, indicates an integrated network. The transition from small-scale to large-scale channels indicates an increase in the amount of flow that could be conveyed through individual channels. Flow in the large-scale channels was augmented by contributary flows from intermediate-scale channel segments that, in turn, were linked with small-scale segments. The wide range of channel sizes, coupled with variable individual channel segment morphology, has an important link with the morphology of residuals demarcated by channel systems.

Channel Orientation and Pattern

Though the regional flow direction was from northwest to southeast, individual channel segments make dramatic deviations from this trend. The variability of channel orientation is particularly apparent when large and intermediate-scale channels are compared. Intermediate-scale channels generally indicate flow from west to east; large-scale channels from north-northwest to southeast. Intermediate-scale channels show deflections of flow consistent with the orientation of the large-scale channels.

The eastern large-scale channel has upstream portions that trend east-northeast for a short distance before being sharply diverted southeastward. The middle portions of this channel are nearly straight, apart from a dramatic channel diversion along its eastern margin (Figure 4-2). Diversion along the eastern margin of this large-scale channel has resulted in bifurcation where down-flow channel segments are orientated eastward to northeastward, becoming indistinguishable in the vicinity of Hamilton Lake. The visible southern limits of this channel splay out into an amorphous, unchanneled zone.

The western large-scale channel (a) is shallow and forms a broad arcuate swath curving towards the east (Figure 4-2). This system begins where two zones of numerous smaller channel segments converge. Immediately down flow from this point, part of the channel splays towards the east as it laterally expands. This channel succumbs to bifurcation around streamlined residuals with a broad, scoured portion along the south and southwest margins, as a result of this expansion. The broad, scoured, western margin is arcuate for approximately 15 km. The eastern portion diverts more sharply, and bifurcates soon after its convergence with the western portion. The diversion of this portion of the western large-scale channel promoted remnant residuals between the two large-scale channels.

Intermediate-scale channel systems are not disconnected, however, from the large-scale systems. The latter provide a highly irregular boundary where large intermediate-scale channels, and their associated residuals, converge. Larger intermediate-scale channels comprise integrated networks between the large-scale channels. A transition of intermediate-scale channel orientation from north to south occurs, resulting in systems that roughly parallel the large-scale channels. In addition to orientation, there is a transition from channels with a wide range of size, to those that are roughly equidimensional (Figures 4-1 and 4-2). Initially, intermediate-scale channels are oriented approximately west to east, with the contributary zones (feeding large-scale channels) being deflected to the south. Deflection by the large-scale channels is reflected in a north-south trend of intermediate-scale forms, this being more consistent with the orientation of the large-scale channels. This general pattern of orientation does not apply to channels in the extreme eastern part of the study area where intermediate-scale channels are deflected northeastwards towards Hamilton Lake (Figure 4-2).

Orientations of small-scale channels may deviate greatly. These are superimposed on the erosional residuals so that their orientations are associated mainly with the forms of the residuals, and their linkages with adjacent intermediate-scale channels. Since the residuals are defined by intermediate-scale channel margins, small-scale channels are generally consistent with their orientations. There is some difficulty in distinguishing small-scale channels from individual scours in parts of the study area.

LARGE-SCALE CHANNEL MORPHOLOGY

Channel Margins and General Characteristics

Large-scale channels are typically broad and shallow with gently undulatory long and transverse profiles. These systems are up to 5 km wide but rarely exceed 20 m in depth. Margins of large-scale channels may be indistinct to very well defined, depending on the nature of the associated junctions. The eastern margin of the eastern large-scale channel is poorly defined in the north where a broad, undulating area grades from the channel. The western margin is sharply defined where residual hills, defined by intermediate-scale channels, converge on the large-scale channel. This channel originates where many smaller systems, oriented west-east, coalesce and the resulting single channel is diverted southward. Southward along the western margin, residual hills extend into the channel and do not display the truncation and curved shape that is apparent further north (Figure 4-1).

Margins of the western large-scale channel reflect somewhat similar characteristics, although the channel is internally more complex. The eastern margin is indistinct to the north where channels have separated from the main system to breach the zone between the two large-scale channels. The western margin is similar to that of the eastern primary channel in that residuals terminate abruptly (Figure 4-2). This is not as striking as in the eastern channel because residuals display tapering tails, though these tails terminate at the channel. Also, residual tails do not curve down flow as dramatically as in the eastern channel.

The western large-scale channel is internally more complex than its eastern counterpart, displaying zones of flow expansion and contraction. Up-channel limits of the western large-scale system originate from a contributary junction, with low junction angle, of two smaller channels. The eastern component begins where west-east oriented channels coalesce and sharply curve southward along the topographic high to the east. The western component originates where numerous, short, channel segments coalesce from a non-channelized zone to the east (Figure 4-2). Progressive channelization of this area developed a broad channel that intersects the eastern component at an acute angle.

The western sector of this large-scale channel is characterized by numerous ridges and furrows that converge slightly towards the junction of the two converging channel sectors. These furrow and ridge assemblages intercept the eastern component at an acute angle, where they are diverted in a direction more consistent with the orientation of the eastern sector. The western component has a steep gradient upflow of the coalescence, but does not obtain the elevation, at the intersection, of the eastern thalweg.

Transverse and Longitudinal Channel Profiles

Transverse profiles of large-scale channels illustrate the undulatory nature of the channel floors. Multiple, longitudinally-oriented, ridges and furrows, down channel from the convergence of the two components of the western large-scale channel, are especially pronounced in Figure 4-3A. These two sectors of the large-scale channel occur at approximately the same elevation (though the eastern component is slightly lower) and are separated by a broad zone of higher ground. Superimposed on this broad zone are the previously described furrow/ridge assemblages that intersect the eastern component of the large-scale channel. The profile illustrates that the furrows are asymmetrical (a), with the steepest portion occurring on the outside of the curving segment. These furrows disappear abruptly on a crest, located at the intersection of the two channel components. At this intersection the greater depth of the eastern sector is possibly a response to the converging channel.

Down flow of the convergence of the two contributing components, this channel displays an arcuate form, curving towards the southeast. Immediately down channel, the eastern component curves toward the eastern large-scale channel. This divergence is characterized by channels that curve sharply toward the east and have up-along-channel gradients (Figure 4-4B). The channel floor is characterized by low, elongated ridges separated by broad, undulating reaches. These ridges partially define the margins of Craig Lake and are abundant in the area upstream from the contributary junction between the two large-scale channels. As this large-scale channel diverts towards the east, distinct lateral expansion occurs, bifurcating around numerous streamlined residuals. Down channel of the convergence of these two components, the channel continues to display the deep furrows initiated by the two contributary components. The western furrow is easily recognized in this cross-section as it is, partially, a result of numerous, smaller, convergent channels. These intermediate-scale channels converge on

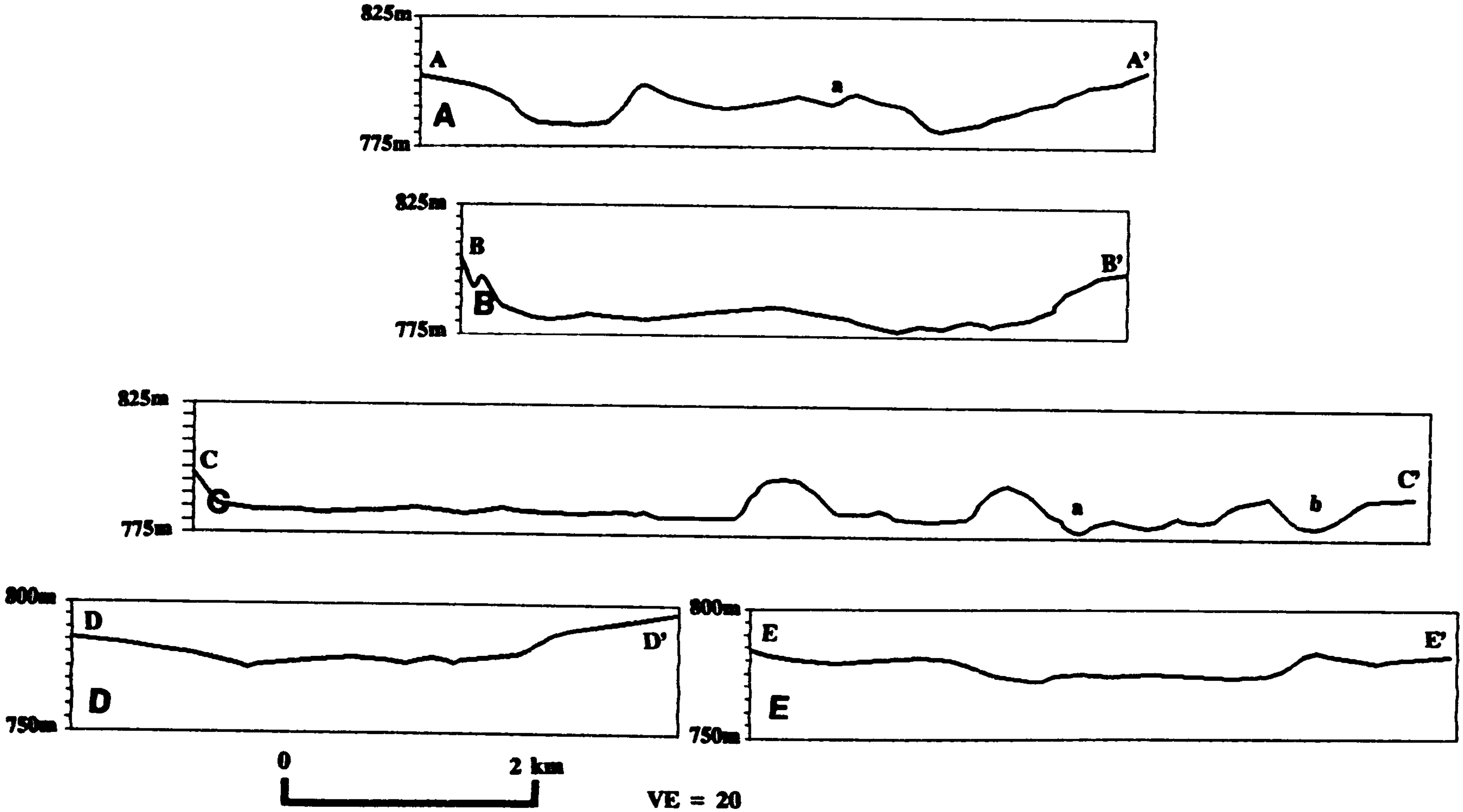


Figure 4-3: Selected transverse profiles of large-scale channels. Lateral furrows dominate the margins of the channels and are associated with smaller ridges and troughs found in the centre of the channel. Locations of profiles are illustrated in Appendix 1. For compilation information see Appendix 2.

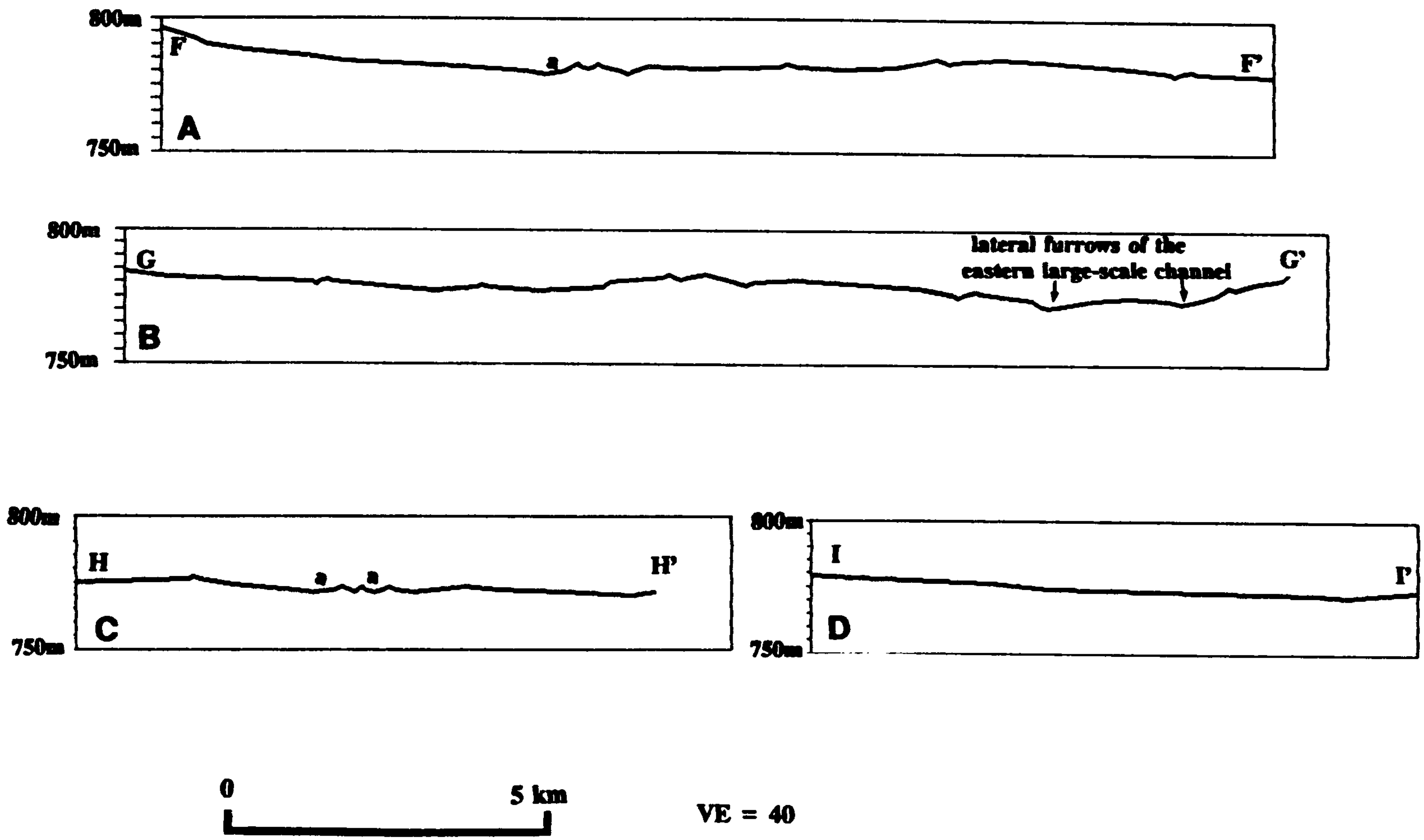


Figure 4-4: Selected longitudinal profiles of large-scale channels. Profiles display the overall gentle slopes of the channels and conspicuous uphill segments and smaller superimposed bed irregularities. For locations refer to Appendix 1. F r compilation procedures refer to Appendix 2.

the large-scale system at high angles. Immediately down channel from this profile the western furrow, present in Figure 4-3A, breaks down into two segments separated by a highly elongated ridge. This ridge conforms to the arcuate form of the gross channel shape.

Figure 4-3B is a cross-sectional profile of the western large-scale channel at the point where divergence and lateral expansion commences, associated with the eastern component of the channel. This is depicted in the convex-up cross-sectional profile (Figure 4-3B) where both components have initiated lateral furrows along their respective channel margins. The two lateral furrows are well developed and are partially the result of contributary channels converging at various angles. On the northern margin of the large-scale channel the lateral furrow has developed troughs and ridges that are diverging down channel. Down channel from this profile the ridges and troughs change into distinct channel forms as further bifurcation occurs around large residual hills. Figure 4-3C shows multiple channel forms that have been created by the lateral expansion and bifurcation of the western large-scale system. Along this profile large residuals are present and, to the north, the channels that resulted from the troughs and ridges are shown. The southern portion of the western large-scale channel adopted a relatively flat cross-sectional profile with only small, highly elongated ridges departing from this trend; the lateral trough, that is striking further up channel, is not apparent here.

The eastern large-scale channel is narrower than the western channel but depicts somewhat similar cross-sectional relief characteristics. This system displays a convex-up cross-sectional profile, with lateral furrows that occur at similar elevations. The furrows are presently occupied by stream channels crossing small topographic divides that are part of the internal variability of the entire channel form. Where furrows are distinct, contributary channel junctions with intermediate-scale channels (western margin) and distributary channel margins (eastern margin) are present. The western furrow is better developed than its eastern counterpart. Together, they define a broad, isolated, medial residual. The surface of this low, medial residual has superimposed on it numerous longitudinal grooves that roughly parallel the channel axis. The southern limits of these lateral furrows occur where the western furrow is diverted eastward (as channels converge from the western large-scale channel). Unlike the western large-scale system, the eastern channel is formed as numerous west-east flowing channels are diverted southward. This diversion appears to have created the two lateral furrows, with the convex-up portion in between.

The western lateral furrow of the eastern large-scale channel is associated with contributary, intermediate-scale channels intersecting nearly at right angles. These distinct lateral furrows, distinct in upper portions of the channel (see Appendix 1), are muted further down channel at the location of Figure 4-3D. However, down channel from 4-3D the western lateral furrow becomes more distinct as channels, diverted from the western large-scale system, converge (Figure 4-3E). Thus, well defined lateral furrows up channel give way to a slightly convex-up cross-sectional profile in the central portion of the system, and the subsequent reestablishment of furrows where channel convergence occurs. Down channel from this second portion of channel with lateral furrows, the channel takes on a relatively broad, flat profile where laterally expanding flow from the western large-scale channel intersected it. Down channel from this zone, distinct channel forms are absent and local relief is determined by enclosed depressions (many of which are in bedrock), aeolian deposits, and gravel deposits.

Longitudinal profiles of large-scale channels illustrate their generally gentle gradients (Figure 4-4). A steep gradient, present in profile F-F', is associated with the western lateral furrow of the western large-scale channel (Appendix 1). At this point the lateral furrow grades to a gentle profile in the vicinity of Craig Lake (a). The depression at (a) is located at the convergence of a prominent intermediate-scale channel. The scour present at this point, and the higher zone down channel, represent erosion introduced at the contributary channel junctions. These undulations can also be seen in Figure 4-4C, (a), where the undulatory thalweg is associated with divergent channel segments. The ridges in this profile represent differential scour that occurred in partially channelized flow at a prominent flow diversion. The lateral furrow that is associated with numerous convergent junctions is shown in Figure 4-4B (in the part of the profile that transversely crosses the channel) and in Figure 4-4C (longitudinal profile).

One intriguing aspect of the scabland is the numerous occurrences of uphill, along-channel profiles. These are common in smaller channel segments (to be discussed later under Residual Crossings and Small-Scale Channels) but are less so in intermediate and large-scale channels. Figure 4-4B illustrates the longitudinal profile of the eastern component of the western large-scale channel. After convergence with the western component, the eastern component diverts abruptly to the east. This diverted portion has a distinct uphill along-channel profile for a large distance, before reestablishing a downhill gradient near the junction with the eastern large-scale system. This portion of the channel, with an uphill gradient, represents a minimum rise of the thalweg found in the channels that compose the diverted portion (channel b in Figure 4-3C, for example). Smaller channels in this sharply curve, following uphill paths for large distances before becoming muted at convergence with the eastern large-scale system (where Figure 4-13B is located, see Appendix 1).

Mesoforms

Large-scale channels reveal a complex, internal system of erosional and depositional bedforms. Bedforms are both longitudinal to transverse in style, while some forms reflect localized interference at channel junctions. Common erosional bedforms found in large-scale channels are longitudinally-oriented grooves and remnant, low-relief ridges that may be several hundred metres in length while having a few metres of relief. Grooves are comparatively straight and parallel for long distances, but some are convergent and divergent. They are usually oriented parallel, or slightly oblique, to the channel axis, but deflection occurs where contributary channels are situated. Longitudinal grooves are common in both the eastern and western large-scale channels wherever extensive, flat, cross-sectional profiles are present, such as the central portion of Figure 4-3B and the southern portion of Figure 4-3C. Individual grooves are found in the central portions of the channels because more effective erosion has apparently been concentrated along the channel margins, forming the lateral furrows. Longitudinal grooves are well represented in large-scale channels, but to a lesser degree in the narrower, intermediate-scale, channel segments. Development of lateral furrows has resulted in isolation of low-relief, inner channel residuals. The low-relief remnant ridges, demarcated by the longitudinal grooves, are mainly located on higher portions of the large-scale channels but have greater relief when located in the lee of a larger residual.

Prominent bedforms in large-scale channels are boulder concentrations. These vary from isolated clasts, through small clusters, to elongated ridge forms. Boulder concentrations, adopting longitudinally-oriented forms, tend to be small and infrequent compared to elongated remnant ridges. A cross-section through one boulder ridge is shown in Figure 4-5A. This ridge occurs in the upper reaches of the eastern component of the western large-scale channel (Appendix 1). Inspection of this ridge suggests that the boulders mantle a more subtle erosional bedrock ridge. Boulder lags are common in all scales of channels in the scabland, though the sizes of clasts and the nature of their concentration differ. Individual boulders are rounded to angular (Figures 4-5B and C), indicating variable effects of fluvial transport and lithologic control. Boulders found in large-scale channels are large, frequently exceeding 1 to 1.5 metres in diameter. Figure 4-5B illustrates a boulder found as a lag in a large-scale channel This boulder is isolated from others of its size and measures approximately 3 metres in diameter. On the proximal end numerous fractures are present, with one large portion of the clast nearly dislodged.

In addition to the large, isolated boulder there are numerous clusters of smaller boulders in large-scale channels. These are typically located on topographically high zones of the channel floors, whereas adjacent lower areas are free of boulders. Boulder clusters are generally oriented parallel to the channel margins, as is the case for the boulders in Figure 4-5A, but some are transverse or non-directional (Figure 4-5C). Transverse and non-directional boulder clusters are associated with expansion zones of large-scale channels, where channel margins diverge and there is little local relief in the channel bottoms. These deposits appear to be 1 to 2 clasts thick where exposed at the distal ends of clusters (Figure 4-5C).

Another type of bedform that characterizes large-scale channels is indicative of zones with broad, shallow channels that have smaller channel forms inset. Where the western large-scale channel takes on an anastomosing pattern, channels occasionally

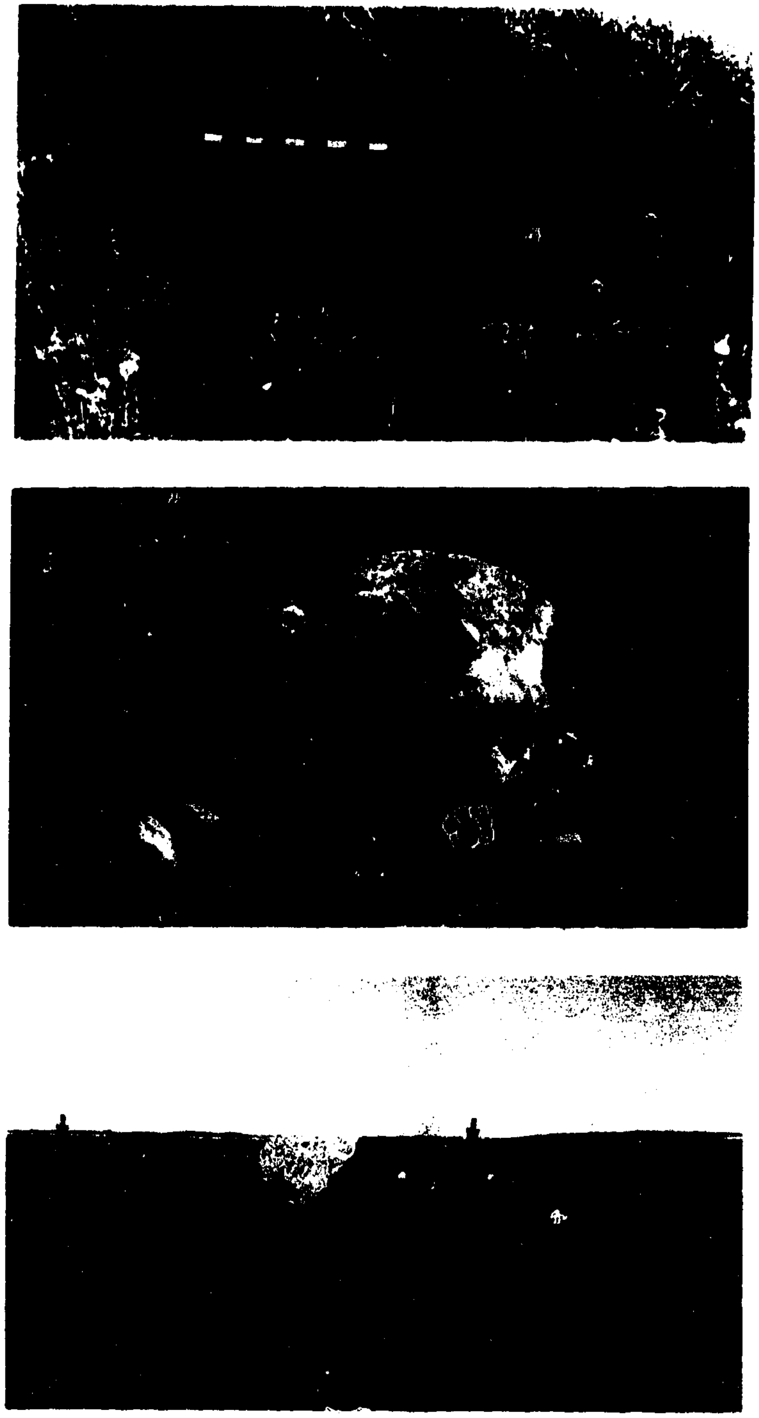


Figure 4-5: Boulder deposits found in large-scale channels. A - Small accumulation of boulders forming a ridge, superimposed on a subtle remnant ridge. B - Large boulder displaying percussion marks on the up flow end, flow from left to right. C - Clusters of boulders. For locations see Appendix 1.

display "herring-bone" bedforms that resemble "V's" inset into one another, pointing up flow (HBB in Appendix 1). "Herring-bone" bedforms are present where lateral expansion of the western large-scale channel resulted in bifurcation around residuals. These forms occur where residuals have generally low relief and where inset channels exist in the larger channel form. "Herring-bone" bedforms are located roughly along the boundary where the two large channels intersect. At this point the channelized forms that characterize much of the scabland are absent.

Shallow scoured zones in large-scale channels occupy areas where intermediate-scale channels converge on the large-scale channels. The amount of scour, and thus the size of lakes that occupy them, was greater where many large intermediate-scale channels intersect the large-scale channel (for example Craig Lake, Figure 4-2). Lakes located in the large-scale channels are so shallow that during times of low water they expose boulder deposits that, typically, form a pavement, similar to that illustrated in Figure 4-13A.

INTERMEDIATE AND SMALL-SCALE CHANNEL MORPHOLOGY

Channel Margins and General Characteristics

Intermediate and small-scale channel segments are characterized by gently sloping margins and highly variable thalweg gradients. These systems are narrower and deeper than the large-scale channels. Intermediate-scale channels display limited sinuosity or may have an anastomosing pattern (for example see northwest of Craig Lake in Figure 4-2). Intermediate-scale channels seldom display margins that truncate channels formed by continuous flow over residual crests. Intermediate-scale channels, and associated small-scale channel segments, represent an intricate, integrated network with numerous hierarchies of channel sizes. Apart from channels located in the southwest portion of the study area (Figure 4-2) few are noticeably isolated from the main channel network.

Slope transitions between channel bottoms, and interfluves separating intermediate-scale channels, are gradual (Figure 4-6) and the systems have perceptibly linked reaches crossing intervening ridges. Thus, intermediate and small-scale channels are integrated such that channels traversing residual hills have thalwegs of the same elevation at both the distributary and contributary junctions. Elevation differences between intermediate-scale channel thalwegs and adjacent uplands are variable up to 20 m. This relief is minimal where channels bifurcate, with the resulting system crossing a residual. The undulatory nature of the terrain, the wide range of channel gradients (and depths), and low relief between channel thalwegs and residual crests, make difficult the delineation of individual channel segments. Margins of intermediate-scale channels manifest themselves as gentle gradients between residual crests and channel floors, with smaller distributary channels branching off.

Transverse and Longitudinal Channel Variations

Straight, intermediate-scale, channel reaches are nearly symmetrical, but segments associated with channel junctions and/or flow diversion, may be strongly asymmetrical (Figure 4-6). Channel (a) in Figure 4-6A displays a marked cross-sectional asymmetry, where the southern margin has a significantly greater slope than the northern margin. The asymmetry was likely created by flow convergence, involving a deeply incised channel and a broad, scoured zone. Interference, where flow from the northwest intercepted the channelized flow, likely caused enhanced erosion of the southern margin. Concentric troughs on top of the flanking residual suggest that rotational slumping has

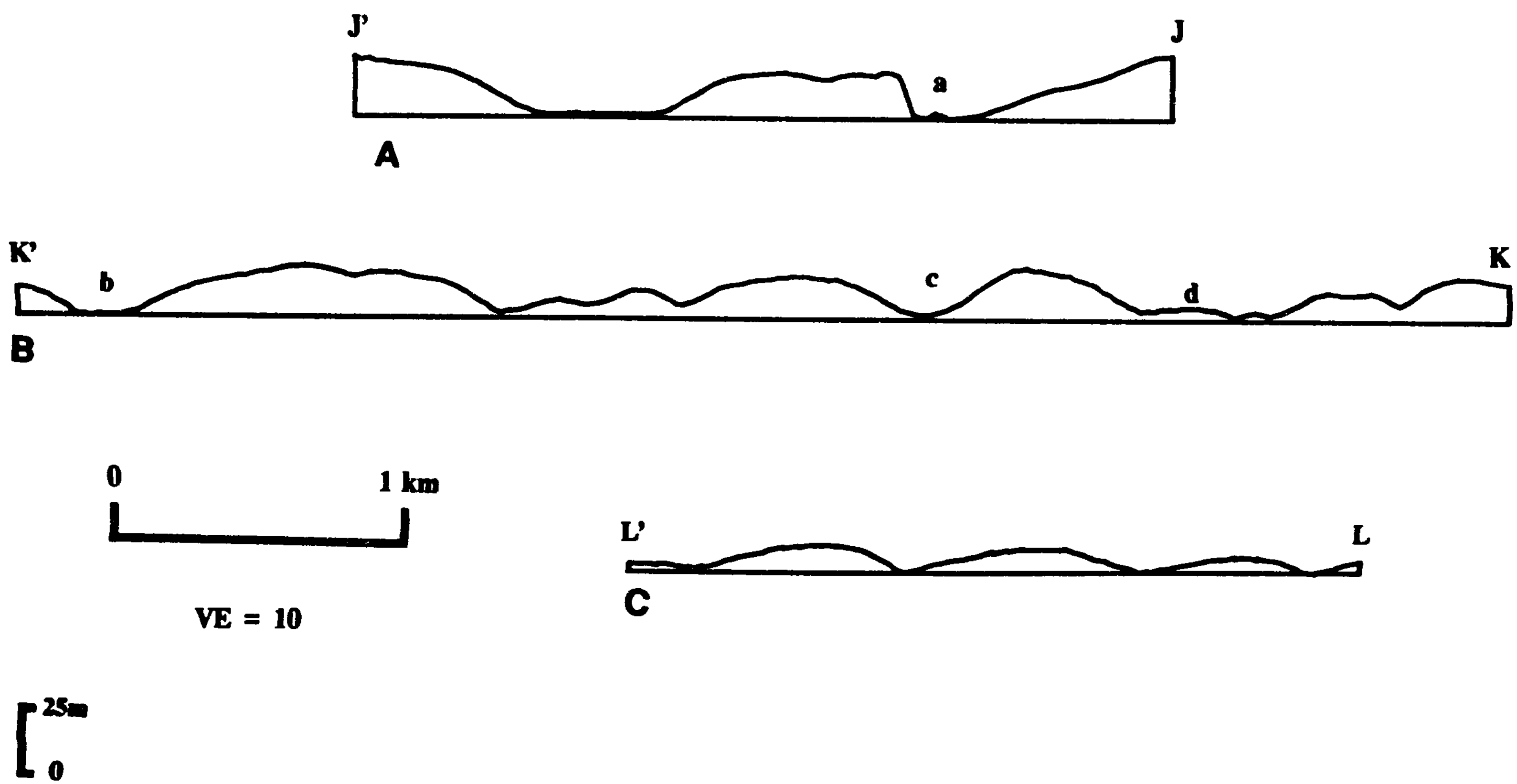


Figure 4-6: Selected transverse profiles of intermediate-scale channels. Channels display variable shapes including a distinctive flat bottom, concave-up and convex-up. For locations see Appendix 1. For compilation see Appendix 2.

subsequently occurred, attesting to the instability of the oversteepened margin. In addition to these characteristics, this particular channel margin has transverse elements superimposed on the adjacent residual, and extensive boulder deposits on the northern margin (refer to Chapter 5).

In most instances, margins of intermediate-scale channels exhibit the subtle transitions shown in Figure 4-6. The channel margins do not have an abrupt slope change separating a zone of non-glaciofluvially modified terrain from the channels. These subtle channel margins are typical in the channeled scabland and are present at all scales. More easily defined channel margins are associated with relatively deep channels. Shallow channels generally display a smooth slope transition between the channel floors and the tops of the flanking residuals. This variability is shown, as in Figure 4-6, where larger, intermediate-scale channels are comparable in size to the residuals (Figure 4-6A and B) or alternatively, appear smaller than the residuals that they dissect, creating an undulatory profile (Figure 4-6C). In both cases, sharply defined channel margins are not present (except for channel (a) in Figure 4-6A, for reasons already discussed).

Transverse profiles demonstrate that intermediate-scale channels possess flat, concave-up, or convex-up cross-sectional profiles. Multiple ridges in a transverse profile are usually associated with contributary channel junctions, though internal perturbations in some channels indicate the presence of smaller erosional and/or depositional bedforms. Figure 4-6 shows a variation of intermediate-scale channel cross-sections where systems with flat floors (b) occur in channels with pronounced concave-up (c) and convex-up (d) profiles.

A convex-up cross-sectional profile is shown at (d) in Figure 4-6B where two small convex-up "knobs" are present. The northern "knob" is associated with a large deposit of boulders, formed at the contributary junction with a smaller channel, whereas the second "knob" is dominant in the profile. This convex-up portion of the channel is flanked by two troughs that partially separate it from residuals delineating the channel margins. The cross-sectional convexity is augmented by numerous clusters of boulders that increase in frequency towards the crest of the low intrachannel residual. This situation is similar to that of the large-scale channels, insofar as the intrachannel residual is flanked by two lateral furrows along the margins of the channel. The similarity also extends to the locations of the boulder deposits, which are relatively numerous near the centre of the channel (i.e., near the crest of the convex-up portion). The convexity of these channel cross-sections suggest incision alo~~ the margins while the centre portions of the channel were partially protected by the boulder mantle.

Flat channel cross-section profiles are common for intermediate-scale channels (Figure 4-6A and B). These are usually associated with channels that have been incised to lower elevations than those with convex-up or concave-up profiles (Figure 4-6B, b). The flat profiles are unlikely to be entirely a result of primary erosion/deposition because postglacial deposition was likely. The depth of sediments is not known. However, where water levels are low, boulder deposits (usually forming a pavement) indicate minimal postglacial deposition. Thus, the forms of the cross-sectional channel profiles are primarily related to the initial erosion, with a minimal amount of post-formational deposition veneering the channels.

Intermediate-sca :hannels having concave-up cross-sectional profiles are generally deeper and narrower than either convex-up or flat-floored channels of the same scale. These channels provide narrow gaps between residuals and show a smooth transition between the channel thalweg and the residual crest.

Intermediate-scale channels have variable gradients reflecting different amounts of scour at contributary and distributary channel junctions. Typically, there are abrupt drops in the channel elevation at points of channel convergence. This is illustrated by Figure 4-7B where channel convergence created a localized, highly steepened gradient. Conversely, distributary channel junctions are characterized by small increases in the height of the channel bed. This is shown immediately up flow from the sharp step in Figure 4-7B and was caused by the partial bifurcation of flow through the channels depicted in Figures 4-8 and 4-9A and B. The influence that contributary and distributary channel junctions had on the relief of a system is also illustrated in Figure 4-7A where an undulatory thalweg occurs. In this channel numerous small residuals are present, in addition to small channels converging from the north. Flow diversion created the differential scour responsible for the nature of this thalweg. The large "high" within the channel is associated with bifurcation of the channel into two roughly equal-sized channels. This "high" is observed to possess a convex-up cross-sectional profile and is superimposed by boulder clusters (Figure 4-6A).

Residual Crossings and Small-Scale Channels

Channels that cross residuals take on various forms. Channel thalwegs are convex-up, concave-up, or involve combinations. The latter have multiple ridges and depressions forming a single, undulatory, channel segment. All of these channels are curvilinear in plan and are associated with numerous contributary and distributary channel junctions.

Residual-crossing channels that have a convex-up thalweg, typically originate at a distributary junction with a larger channel. After bifurcation, the channel takes on a curvilinear plan shape. This is illustrated by Figure 4-8 where channel divergence occurs

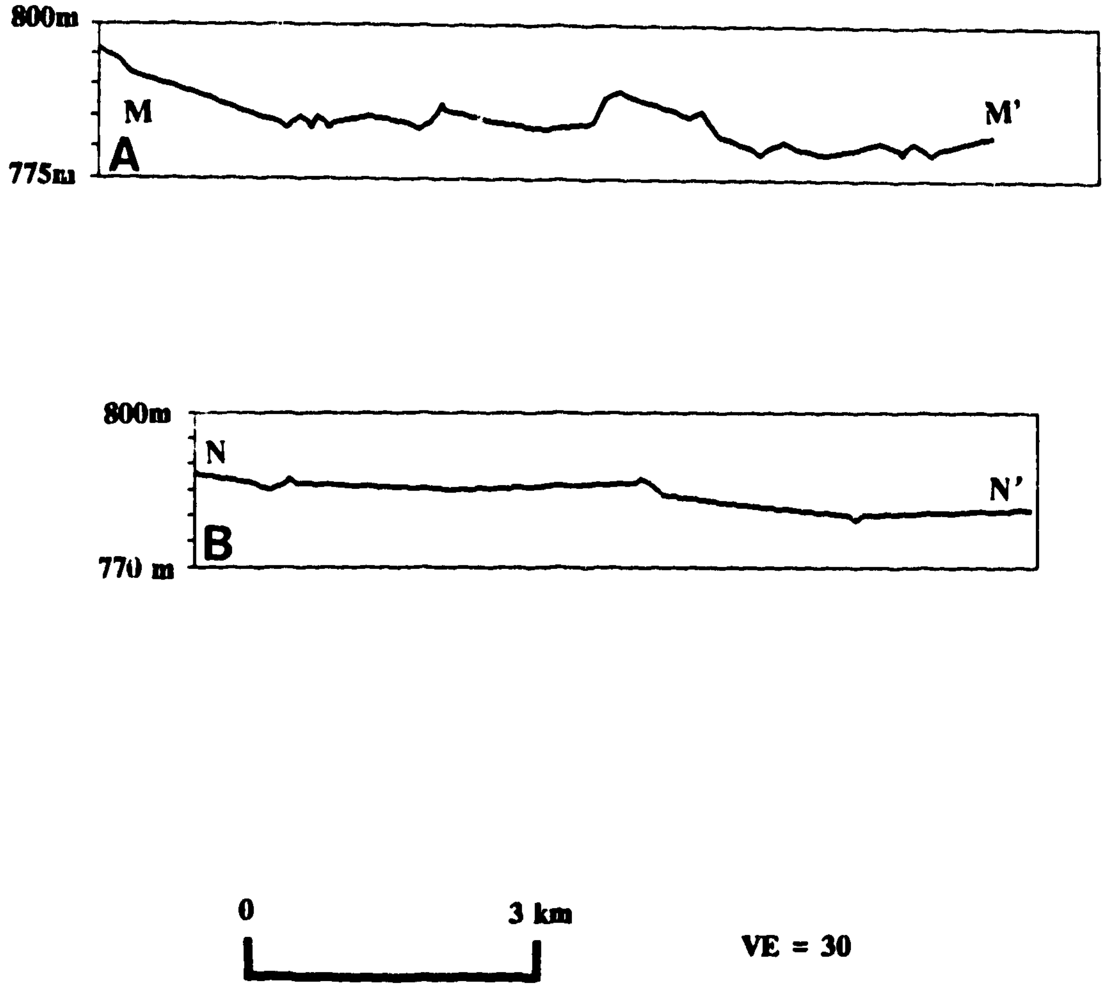


Figure 4-7: Longitudinal profiles of intermediate-scale channels. Undulations in the profiles are the result of numerous contributary and distributary junctions concentrating erosion during formation. For locations see Appendix 1. For compilation information see Appendix 2.

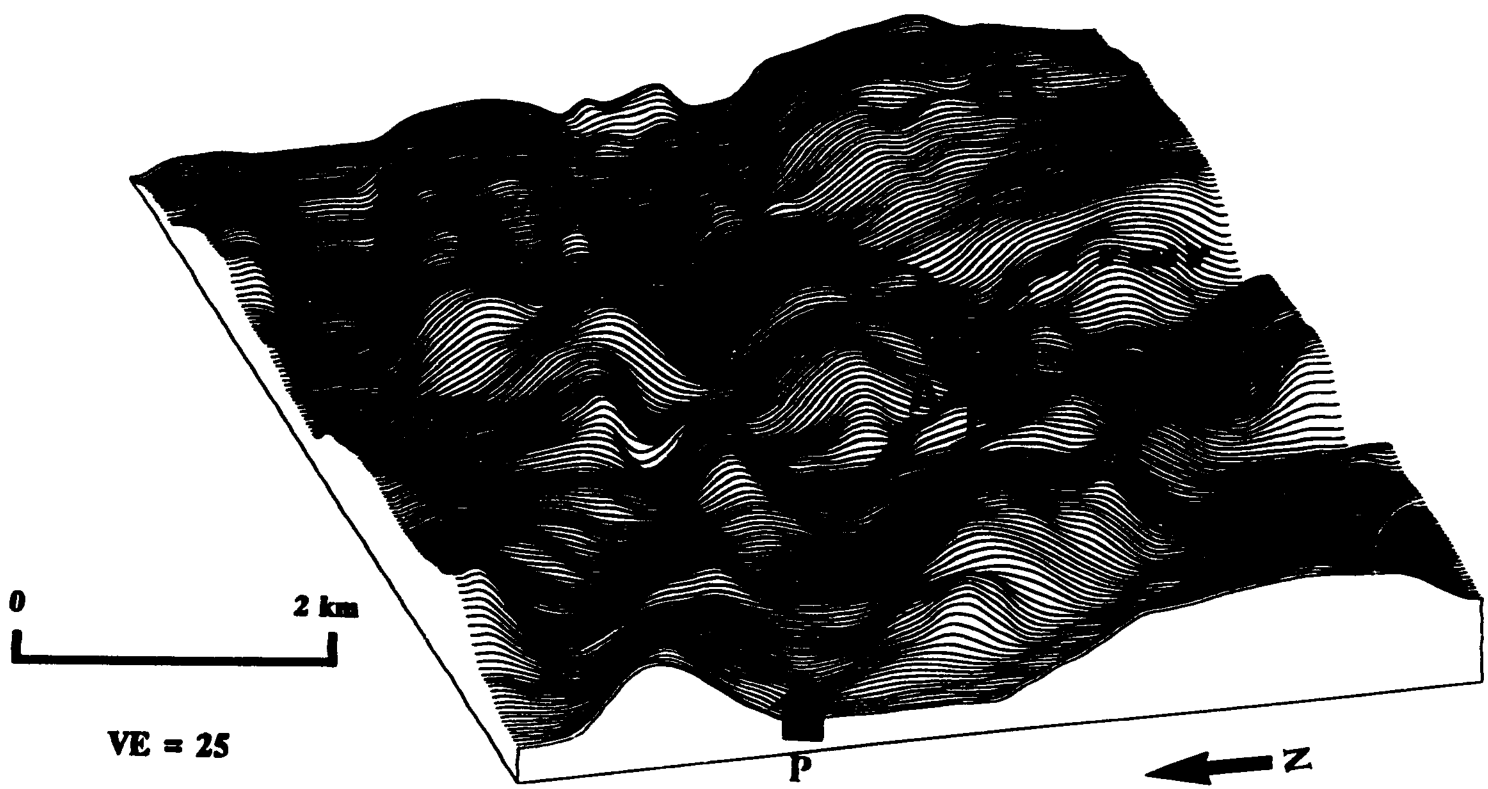


Figure 4-8: Locations of profiles in Figure 4-9. P - paleoflow direction. See Appendix 1 for location and Appendix 2 for compilation procedures.

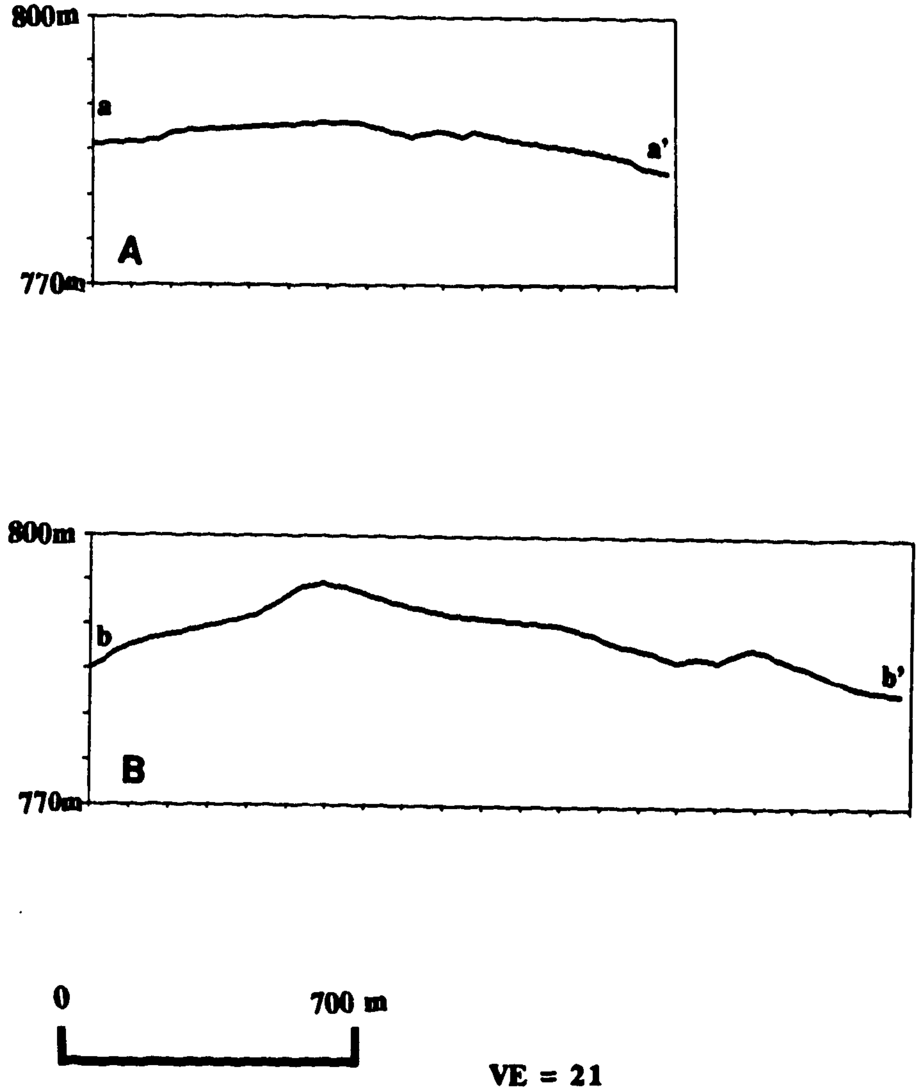


Figure 4-9: Convex-up along channel profiles with small superimposed undulations, associated with residual crossings. For compilations procedures see Appendix 2.

at a slight bend in the larger channel. Three smaller channels are diverted over the residual and rejoin in an enclosed depression. The along-channel profiles of these channels (Figure 4-9) illustrate the concave-up thalweg and the incision that has occurred in channel a-a'. Channels a-a' and b-b' display a well developed, convex-up, along-channel profile in which the thalweg rises to substantial elevation, given the overall subtlety of the landscape. In addition to these three well developed channels, several other more subtle expressions of channels are present. One climbs the residual on the proximal end, separating two portions on top of the residual at (c).

Concave-up channel reaches also occur up flow of some channel bifurcations and in association with contributary channel junctions. An example of scour that occurred up flow from a channel bifurcation is shown in Figure 4-10 Here, a small channel longitudinally traverses a large residual and produces an enclosed depression immediately up flow from the obstruction at (a). This example of thalweg concavity appears not to be associated with a contributary channel junction but, rather, is the result of convergent, unchannelized flow over parts of the residual. Scour that produced the concavity occurred up flow from possible lateral sources at (b) and (c). Thalweg concavity is common in the channeled scabland, but is usually found in conjunction with some contributary channel junctions, and in channel segments with undulatory along-channel profiles.

Channel reaches with undulatory thalwegs are typically associated with channel convergence that appears to have altered predominantly convex-up channel segments. Enclosed depressions are found immediately down flow of the convergences. Figure 4-11 shows channel (x) converging with the channel represented in profile a-a'. Scour produced a concave-up portion of the predominantly convex-up channel segment (Figure

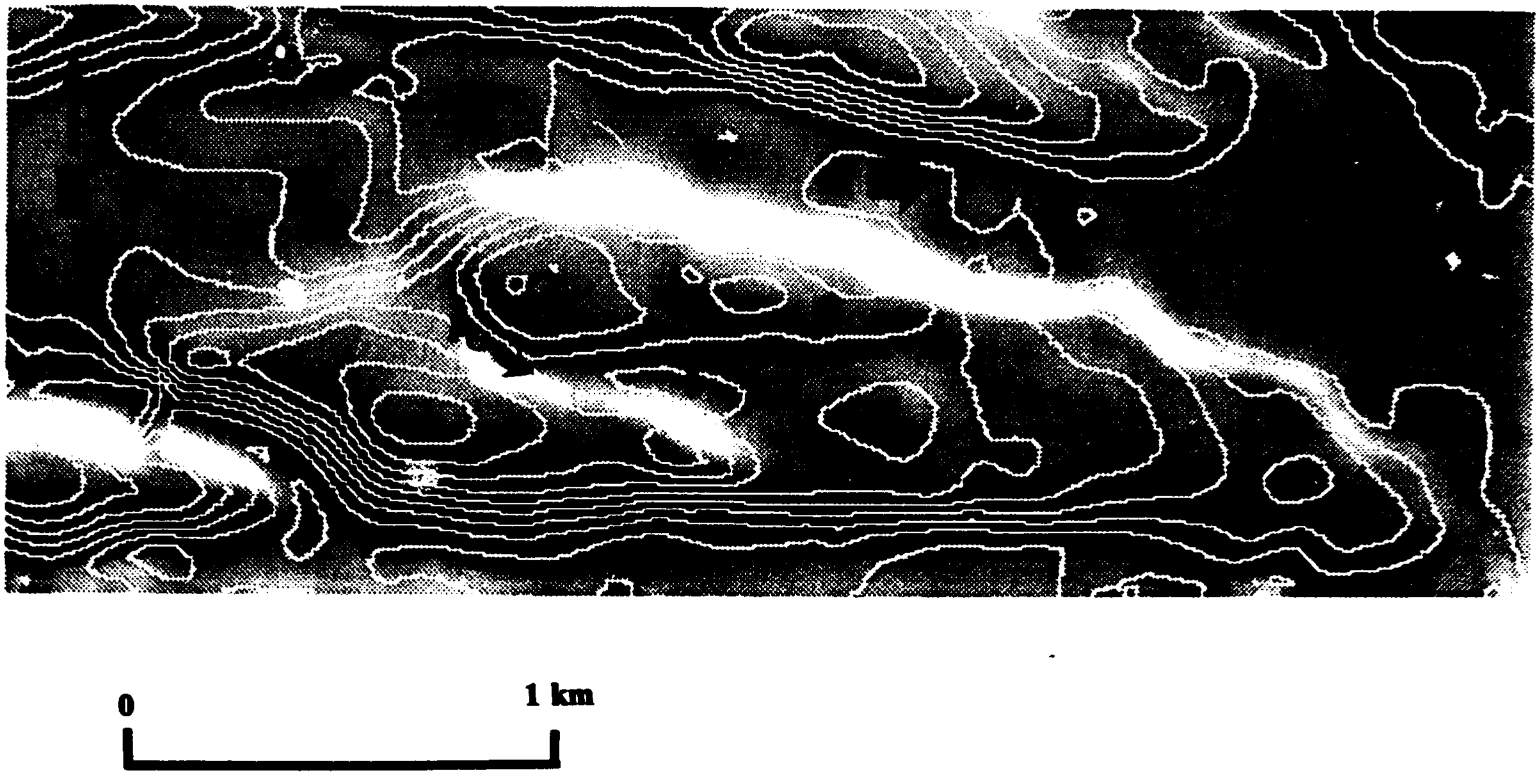


Figure 4-10: A perched channel (pc) possesses a large scour (s) upflow from a low obstruction at (a). Unchannelized flows over the side of the residual are thought to be responsible. P - general flow direction. Contour interval = 2 m. See Appendix 1 and 2 for location and compilation information.

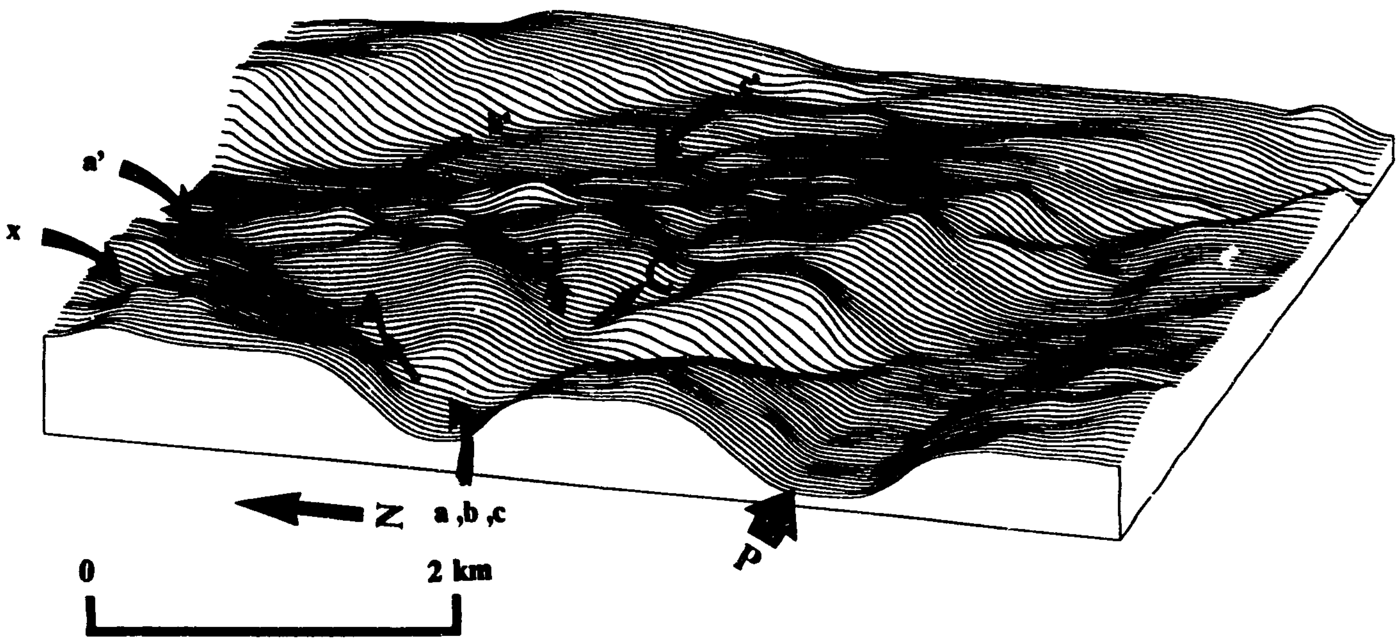


Figure 4-11: Locations of profiles in Figure 4-12. Note the small channel that is intersecting channel a-a'. P - paleoflow direction. VE = 15. See Appendix 1 and 2 for location and compilation information.

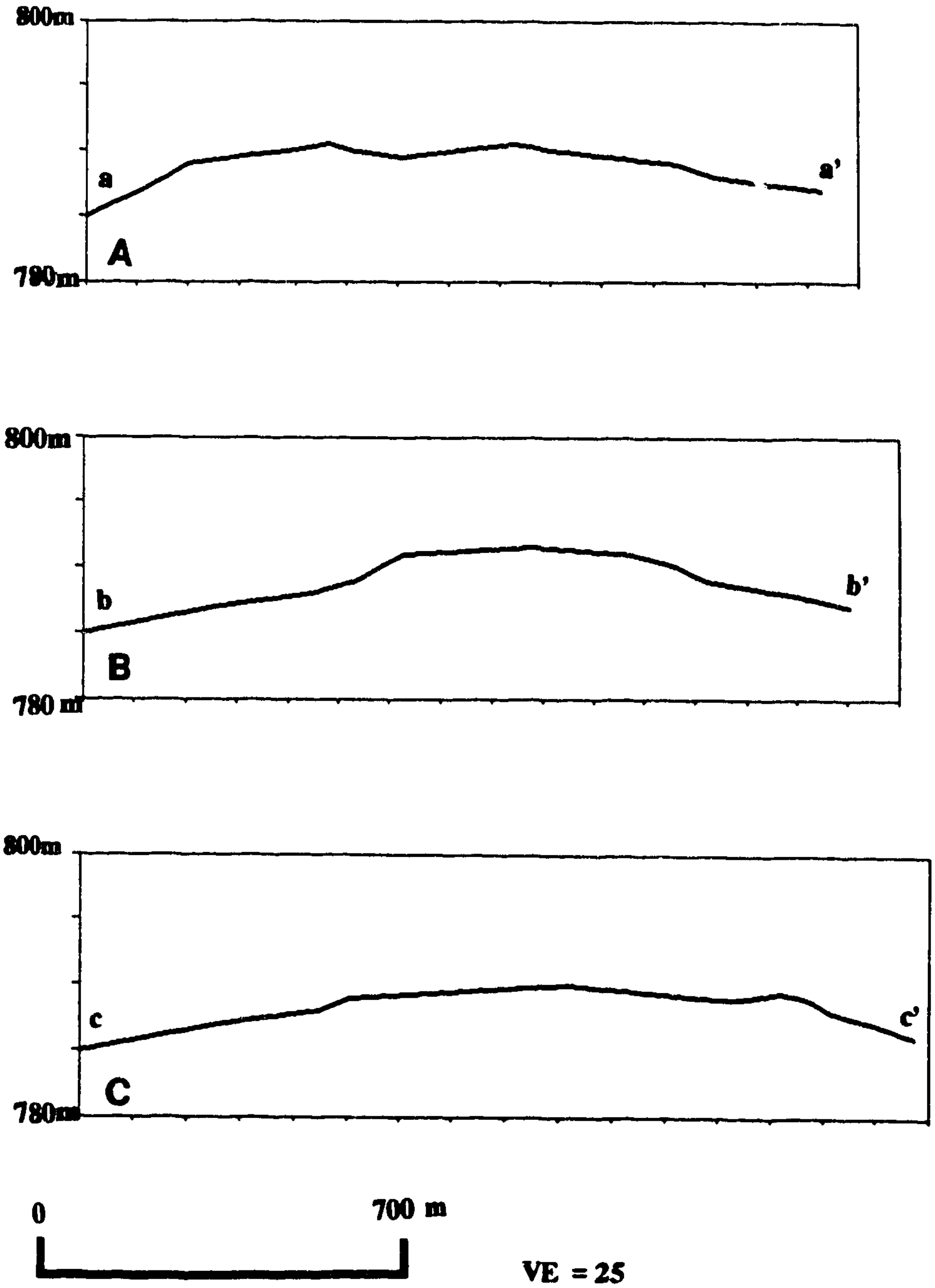


Figure 4-12: Undulatory along-channel profiles for residual crossing, small-scale channels. For compilation information see Appendix 2.

4-12). Undulatory channel thalwegs are associated with channels that have contributary and/or distributary linkages with other channels. Uphill channel segments are typically located down channel from a bifurcation (for example, see Figure 4-12), whereas, downslope channel segments are usually associated with contributary junctions. The anastomosing channel pattern provides many such junctions, and thus numerous occurrences of undulating thalwegs in intermediate-scale channels.

Mesoforms

Intermediate and small-scale channels do not display many of the erosional bedforms that are common in the large-scale channels. Bedforms in these systems are, predominantly depositional, composed of boulder clusters. Erosional bedforms are restricted to small scour pools that appear to be more a result of convergence of channels and/or sheet flow, on a particular channel, than on the flow present in any one channel. Small erosional residuals, that are present in some channels, are usually isolated knobs that are found to be mantled by boulders. Depositional forms occur as heterogeneous-sized deposits along channel margins (Figure 4-13A), pavements that cover the entire channel (Figure 4-13B), or thin mantles on small residuals (Figure 4-14). Boulders are commonly found in concave-up portions of residual-crossing channels, with the intervening "highs" having only scattered occurrences.

SUMMARY

Channels of the Coronation-Spondin scabland represent an integrated network that displays a wide range of morphological characteristics. Numerous channel junctions occur between systems of greatly different scales, where depressions in the along-channel profiles attest to enhanced scour as a result of the flow convergence. These channels are

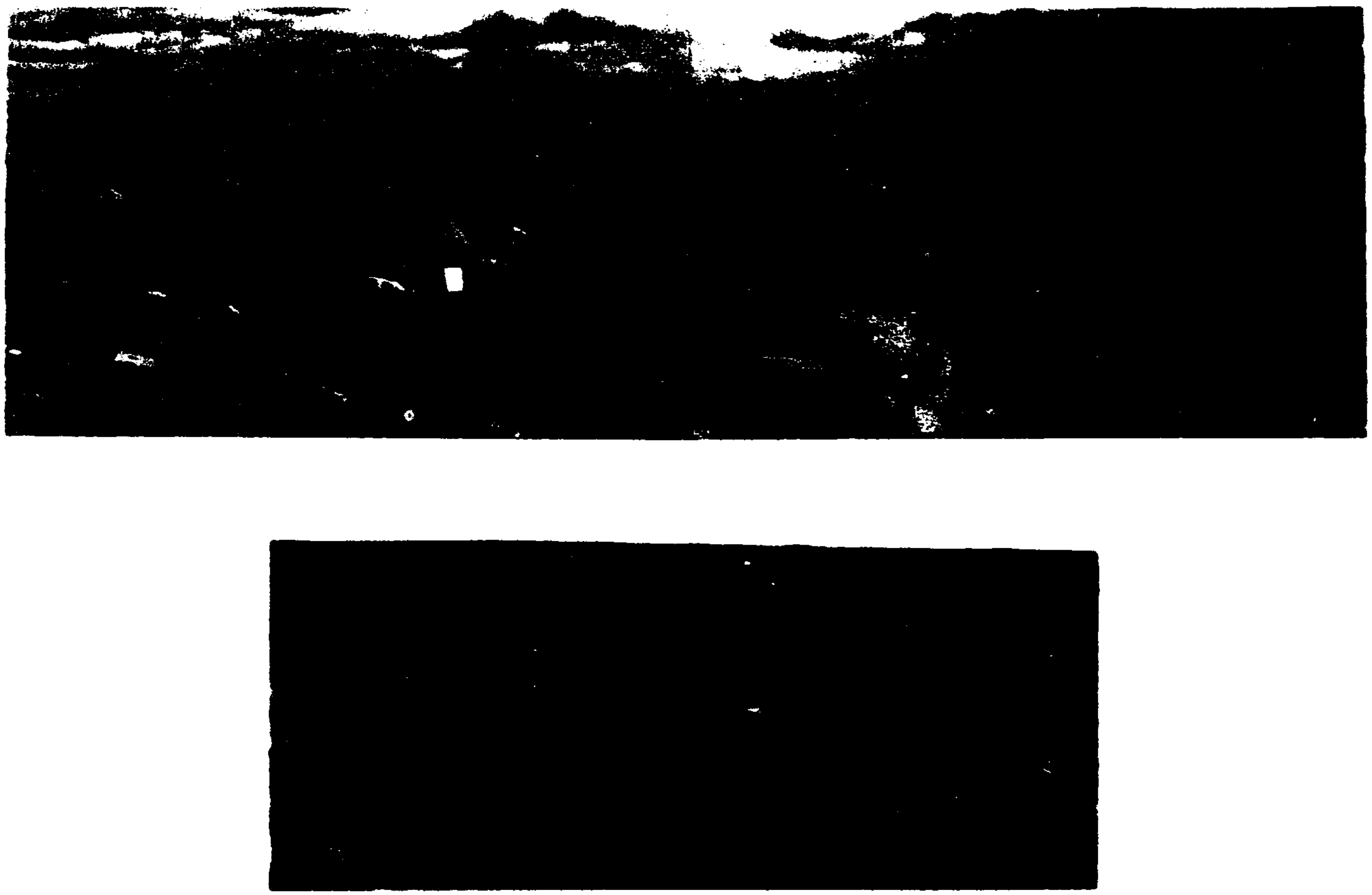


Figure 4-13: Boulder lags found in intermediate-scale channels. A - Boulders may by relatively angular and found in heterogeneous lags. B - Boulder pavement found in a channel at the convergence with the eastern large-scale channel. See Appendix 1 for locations.

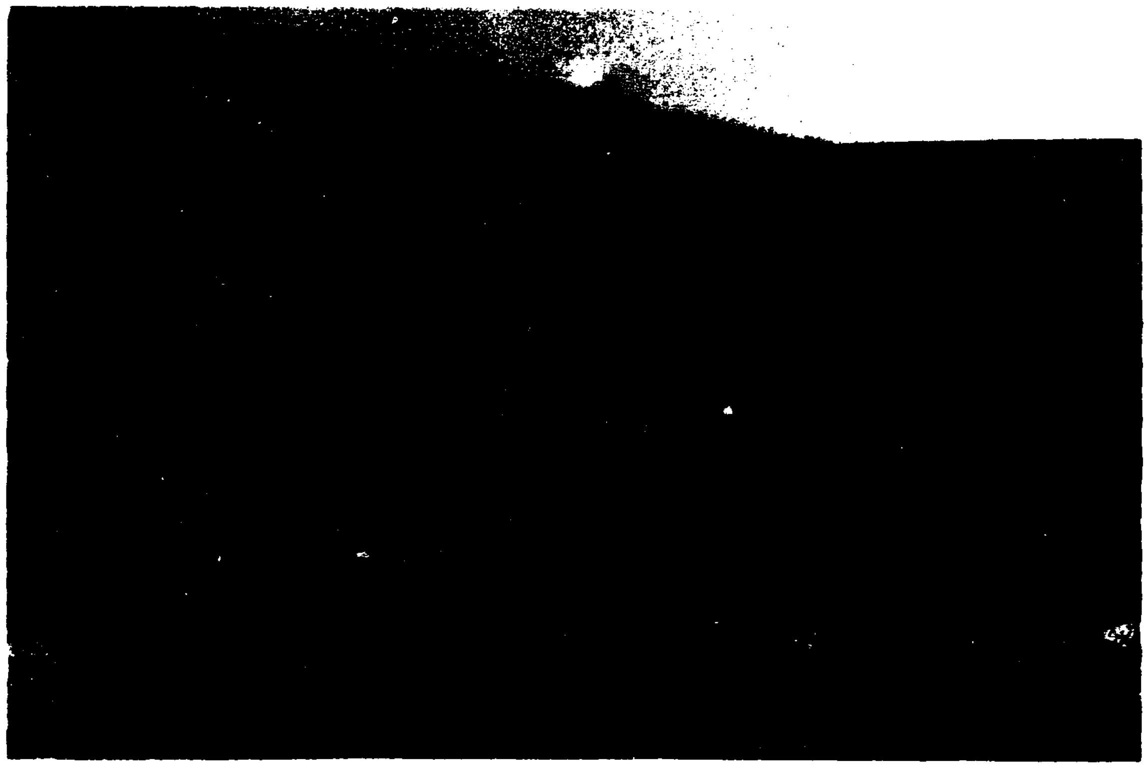


Figure 4-14: A small residual found with a thin mantle of boulders. Presence of bedrock in the roadcut attests to the thickness of the mantle.

found to have uphill gradients, for large portions of their length, associated with numerous channel bifurcations. Gravenor and Bayrock (1956) have suggested that mass movement of till into channels created undulating thalwegs in channel systems further north, however, in the scabland convex-up portions are incised into bedrock. Large-scale channel bifurcation was associated with lateral expansion of the channel width, plus high-angle confluences with well developed smaller channels. The eastward divergence of the large-scale channels was superimposed on the general southeastward flow direction.

Large-scale channels contain longitudinal scours that are associated with deposits of large boulders. Boulders in the channels often occur in clusters or pavements that appear to be related to the size of the channels in which they are found. "Herring-bone"-shaped bedforms exist in areas with numerous channel orientations. Flow interference, as channels intersected, likely caused this pattern. Similar shaped bedforms have been documented by Allen (1968).

The observations presented, on the morphology of channels in the scabland, characterize an integrated channel network that was formed by intense glaciofluvial erosion. High velocity flows were undoubtedly responsible for formation of the large-scale channels which, linked with the smaller channel forms, indicate a formational environment that was typified by flow interference as rapid incision and flow cessation occurred.

CHAPTER FIVE: MORPHOLOGY OF RESIDUALS

INTRODUCTION

The Coronation-Spondin scabland is an integrated channel network characterized partly by highly variable channel sizes and orientations. This inherent variability of the scabland, is also characteristic of the shape of residuals, the margins of which are defined by the channels. Large-scale channels define the boundaries of three main zones of residuals. These zones do not reflect different channel-forming events but, rather, are zones that have experienced less channel dissection than the large-scale channels. The integrated nature of the scabland landforms indicates that large-scale channel[s] [re]present areas of intense erosion, whereas, the intervening zones represent less intens[ive] [illegible]. Thus, descriptions of residuals, formed largely by highly variable channeliz[ation], are imperative for understanding the processes that led to scabland evolution in the study area.

RESIDUAL ZONES

Channel Dissection and Residual Orientations

The morphology of incised channel segments is highly variable, creating zones of residuals that reflect this variability. Large-scale channels divide the scabland into three zones of residuals (Figure 5-1). Residual shapes and sizes were controlled by the pattern and morphology of channels. The residual zones are generally oriented northwest to southeast, although their separation is poor in the upper reaches of the large-scale channels, where coalescent, smaller, channel segments form the two large-scale channels.

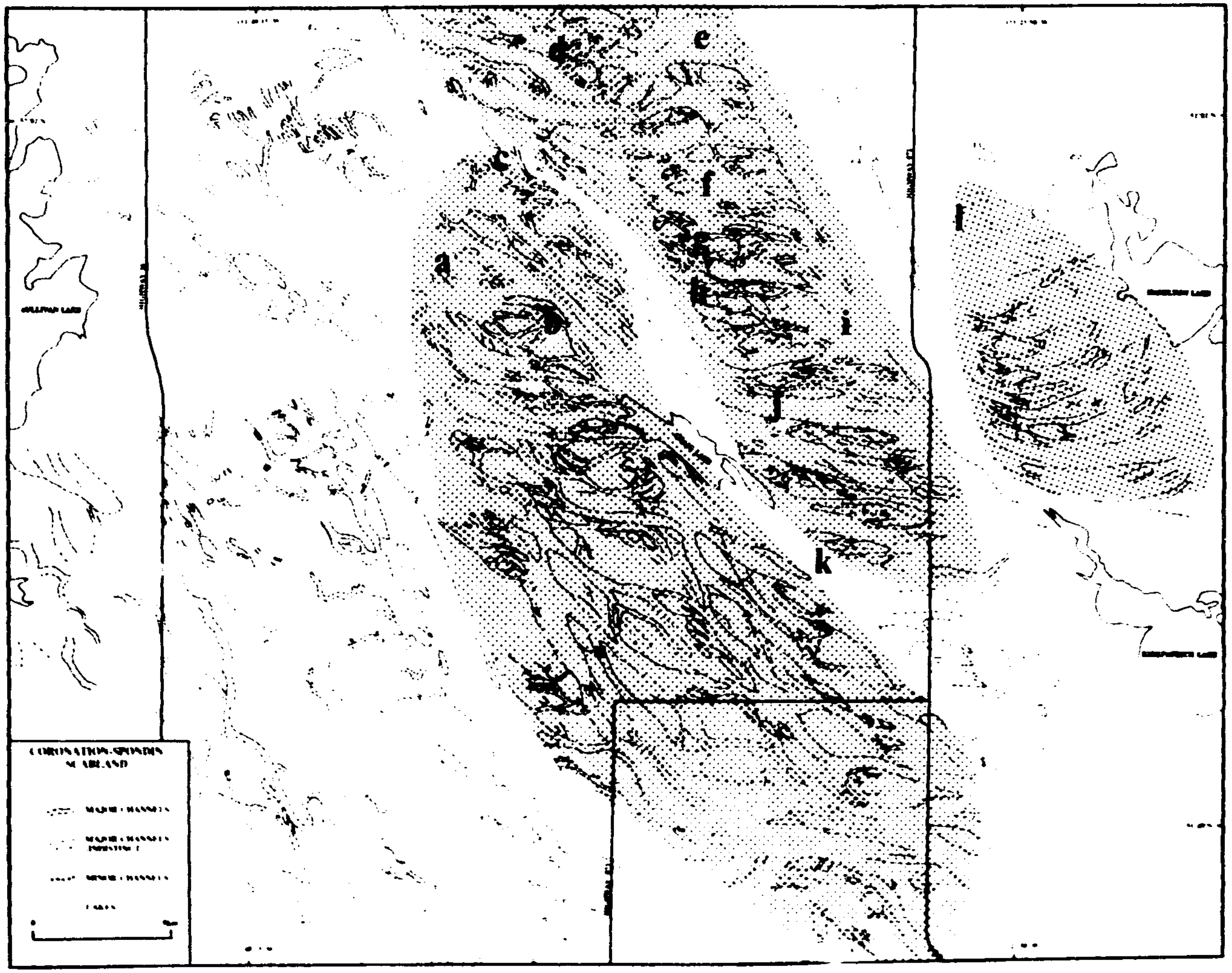


Figure 5-1: The three major residual zones that form the scabland. Refer to text for locations a - l. Compiled from 1:31680 air photos (see Appendix 2).

Western Zone

Residuals in this zone are delineated by intermediate-scale channels that are mainly oriented west-east. The channels form contributary linkages with the western large-scale system. In the northern portions of this zone, residuals are isolated in a broad scoured zone that is the western sector of the western large-scale channel. Residuals are separated by wide tracts of slightly undulating ground where bedrock is frequently exposed at the surface (Figure 5-1a). Isolated residuals are of low relief and display streamlined shapes, with only minor, oblique, residual crossings (small channels that traverse residuals). Further south, west-east trending residuals formed as narrow channels dissected terrain adjacent to the large-scale channel (Figure 5-1b). These residuals have irregular shapes such that an elongated, curved residual is found adjacent to a nearly triangular-shaped residual. In this area numerous, superimposed, channel forms trend obliquely or longitudinally across residuals. Immediately northwest of Craig Lake, residuals are highly elongated, with channels that are oriented almost directly west-east. These residuals have numerous low-relief crossings that connect nearly-parallel channels prior to their confluence with the large-scale channel. West of Craig Lake residuals are well defined by the deeply-incised anastomosing channels. Residuals take on a curved appearance as the anastomosing channel network follows a slightly arcuate path toward Craig Lake.

Southwest of Craig Lake, residuals assume different orientations. A gradual transition occurs from residuals generally oriented west-east, to those with a northwest-southeast orientation. Residual margins are poorly defined compared to those north and west of Craig Lake. These faintly defined residual margins are associated with flanking channels that are shallow and wide compared to those further north. In addition to the transitional orientations, the residuals have broad residual crossings that separate smaller ones superimposed on the larger form. The orientation of residuals in this area is consistent with the orientation of the large-scale channel. This agreement of residual and large-scale channel orientation is apparent as eastward diversion and lateral expansion of this channel occurs. The southeastern portions of these residuals terminate at the confluence of the two large-scale channels. In this zone the residuals and channel forms curve southward before becoming indistinguishable in a broad amorphous zone of undulating terrain.

Along the western margin of this residual zone, marked by the western limit of channels included in the scabland channel network, a large residual shows little channel dissection. It is flanked on the west by a large channel that has indistinct linkages with the scabland channels further east, and with only minor channel crossings at the ends. This residual, apart from the minor crossings and faint channelized connections, appears to be isolated from the main portion of the scabland.

Central Zone

Residuals that compose the central zone are associated with those of the western zone, particularly in their northern sectors. A transition from broad scoured zones (that typify the area northwest of the scabland), to the integrated channel network, occurs along a narrow belt. Southern portions of this transition zone (Figure 5-1c) contributed to channelization of the western large-scale system (and intermediate-scale channels to the west), and the northern portion (Figure 5-1d) contributed to the eastern large-scale channel. Separating these two contributary zones are several large residuals up to 5 km in length. These are slightly curved toward the northeast and have numerous superimposed channels and smaller residual forms. The orientation of these superimposed forms is generally along the axis of the residual. North of these large, curved residuals smaller ones occupy a broad area in which long-axial orientations are roughly toward the east-northeast. This cluster of smaller forms grades into a broadly scoured zoned where few residuals are present, up flow of an abrupt southward diversion (Figure 5-1e).

South of the large residuals that separate these two contributary zones there is another broadly scoured area with few residuals (Figure 5-1f). In this scoured area residuals are oriented west-east and are slightly offset from each other, indicating flow diversion around them in a localized anastomosing pattern. To the south, channel dissection was comparatively ineffective, and residuals are separated by narrow, shallow channels. This area continues nearly as far south as Craig Lake where diversion of the western large-scale channel abruptly changed residual characteristics. Within this area there is an alternation of long, elongated residuals (Figure 5-1g) and intervening areas of smaller residuals (Figure 5-1h). Larger residuals, oriented west-east, display numerous residual crossings that lie at oblique angles to the long axes of the "highs". Between these larger residuals are narrow areas of smaller ones oriented west-east, reflecting an anastomosing channel network of variable complexity. The frequency of recognizable crossings of large residuals appears to decrease from west to east. Channels that define the large residuals, and zones of smaller residuals, are shallow, and frequently have indistinct junctions. The character of channel incision imparts subtle undulations to the landscape that become indistinct where contributary junctions with the large-scale channel occur (Figure 5-1i).

An abrupt change takes place southward, from the subtly-dissected terrain, to an area that is characterized by deep channels and high residuals. This transition occurs where the diverted western large-scale channel crosses the zone separating it from the eastern large-scale channel. In this area numerous bifurcations of the diverted channel segment occur, resulting in channel segments that have uphill, along-channel profiles (Figure 4-4B). These bifurcations are associated with highly elongated residuals that are oriented west-east. To the south these elongated residuals are interrupted by a broad scoured zone that represents a large portion of the large-scale channel diversion (Figure 5-1j). South of this diversion, residuals are larger, with greater local relief and orientations that trend more to the southeast than residuals north of this deeply scoured, diverted channel. These residuals show numerous crossings that occur at high angles to the long axis of the residual. Smaller residuals in this area are found in clusters on a larger form, and are arranged such that flow was conveyed between them. Numerous superimposed forms show a wide range of orientations associated with the channelized crossings of the residuals. This residual zone terminates where the southern portion of the diverted western large-scale channel forms a broad, scoured zone. This transition toward the scoured zone is characterized by an indistinct cluster of residuals. At this transition, northwest-southeast oriented residuals, that delineate the western and southern margins of the western large-scale channel, are separated from the southern extents of the central residual zone by the broad, slightly undulating portion of the western large-scale channel (Figure 5-1k).

Eastern Zone

The eastern zone is located between the eastern large-scale channel and Hamilton Lake. The northern extent of this zone is characterized by undulating terrain with numerous enclosed depressions and small local relief (Figure 5-1). The few channel forms in this area are shallow and discontinuous. A southward transition into an area of distinct residuals is abrupt, as channel segments diverge from the large-scale system. Residuals in this zone generally curve towards Hamilton Lake. Along the margin of the large-scale channel, residuals are oriented slightly oblique to the channel orientation. Numerous residual crossings separate these small, marginal residuals from longer, curved residuals that display increasingly greater angles of divergence from the orientation of the large-scale channel along their length. Most residuals are highly elongated. Those that are not, occur at this abrupt transition along the large-scale channel margin. Along this transition, channel segments have numerous contributary and distributary junctions around residuals. Residuals become broader and wider distally. The southern margin of this residual zone is determined by the eastward divergence of the eastern large-scale channel, as it converges with its western counterpart in the vicinity of Kirkpatrick Lake.

Residual Size

In addition to various orientations, residual sizes are also variable throughout the scabland and illustrate several general trends. In the western residual zone there is a transition from residuals that are small, with sharply-defined margins, to those that are considerably larger, with margins that are indistinct. Northwest of Craig Lake residuals are small, and defined by narrow, channel segments. Further south, a transition from smaller to larger residuals is apparent as a change in relief between the channel floor and the residual crest delineates the residuals. West of Craig Lake, local relief between residual crests and channel floors is seldom less than 15 m, whereas further south it is seldom greater than 10 m. An increase in residual area, decrease in relief, and gentler marginal slopes combine to make residuals further south less distinct than those west of Craig Lake.

In the central residual zone there is no apparent trend in residual size. Schematic variations in residual size typify the zone, such that small residuals often occur adjacent to much larger ones. Very large residuals, further north, are associated with separation of the regional channel pattern.

Large residuals, defined by narrow channel segments, are separated by zones of much smaller residuals that are defined by anastomosing channels. Crossings of the large residuals occur at acute angles, and often isolate secondary residuals. Intervening zones have variable sizes, with low local relief. Crossings on larger residuals have provided links between adjacent anastomosing channels. There is also a transition from west to east between numerous well-defined residuals and an area devoid of residuals. There is a gradual transition to this amorphous zone as channel networks fade.

Residuals associated with the large-scale channel divergence are large, reaching 5 km in length. Numerous residual crossings dissect larger residuals into smaller forms, while the original outline of the form remains as a slightly higher area above the channel floor. These composite forms are highly elongated, with portions of the diverted, western, large-scale channel segments defining their margins.

The eastern residual zone is less areally extensive and does not have a marked trend in residual size. Residuals found along the large-scale channel margin are smaller because they are associated with residual crossings that separate them from larger forms. Apart from this, size of residuals is consistent, though longer residuals occur further south. Large residuals in this zone commonly have narrow proximal ends, widening distally as relief of the form merges with the flanking channel.

RESIDUAL FORMS

Range of Forms

Variability of channel morphology in the Coronation-Spondin scabland has resulted in numerous erosional forms indicative of the character of the flows that were conveyed within the channels. Anastomosing and linear patterns reflect forms that range from sinuous to highly elongated streamlined types. The power of the flow, conveyed in the channels, in addition to the channel widths, have had an influence on residual shapes. Highly-elongated streamlined forms are typically associated with large-scale channels, whereas comparatively short, slightly curved, or sinuous residuals, are associated with narrower intermediate-scale channels. Highly-elongated residuals are also found in association with intermediate-scale channels, where distributary and contributary junctions occur at low angles. Residual shape is dependent partly on the incident angle of channel junctions and on channel segment sinuosity. The planimetric shape of residuals is also dependent on the confluence with large-scale channels. Residual "tails" are observed to extend into the channels. Some were unaltered by the influence of the large-scale channels, but others were deflected down-channel in the direction of flow, or abruptly truncated at the confluence.

Residual margin "sharpness" is determined mainly by the adjacent channel's depth. Usually, proximal ends of residuals are well defined, whereas distal portions may be indistinct where the residual "tail" tapers off. This tapering is associated with channel segments becoming shallow and broad. However, this is not always the case, because residuals occasionally are well defined on the distal end, but merge gradually with the flanking channel on the proximal end. These residuals are usually associated with steep flanking channels that originate, roughly, at the same elevation as the top of the residuals, becoming deeply incised along their sides. Three groups of residual shapes are discernible in the channeled scabland. The first group is characterized by curved or polygonal forms, the second by streamlined or straight residuals, and the third by clusters of closely-spaced residuals.

Curved Residuals

Curved residuals are delineated by narrow, deeply incised, anastomosing channel segments (typical in the western part of the scabland) or by broad, nearly parallel, channel segments such as those that characterize channel divergence toward Hamilton Lake (Figure 5-2). Because residuals are defined by the flanking channel segments, the residual forms reflect the types of flow that existed within the channels at the time of their formation. Convergent and divergent channels, characterizing the western part of the scabland, are somewhat similar to those of braided rivers, except that the related residuals are almost entirely erosional, with only minor deposition in the lee of obstructions offered by the residual forms.

Channels that cross curved residuals generally originate on the inside of residual bends. The crossings occur at various incident angles, and commonly curve so that the distal-crossing channel segments are deflected toward the downflow end of the residuals. These arcuate sub-systems often occur in sets, where two or three small channels are nearly parallel. The along-channel profiles of multiple channel crossings were illustrated earlier (Figures 4-9 and 4-12) and possess convex-up or undulating thalwegs, with elevations comparable to those of both divergent and convergent channel junctions. Broad, subtle, residual crossings are numerous, imparting a dimpled appearance to the residuals where several small residual forms are superimposed on the larger forms (Figure 5-3). Residual crossings determine a hierarchy of residual forms whereby the

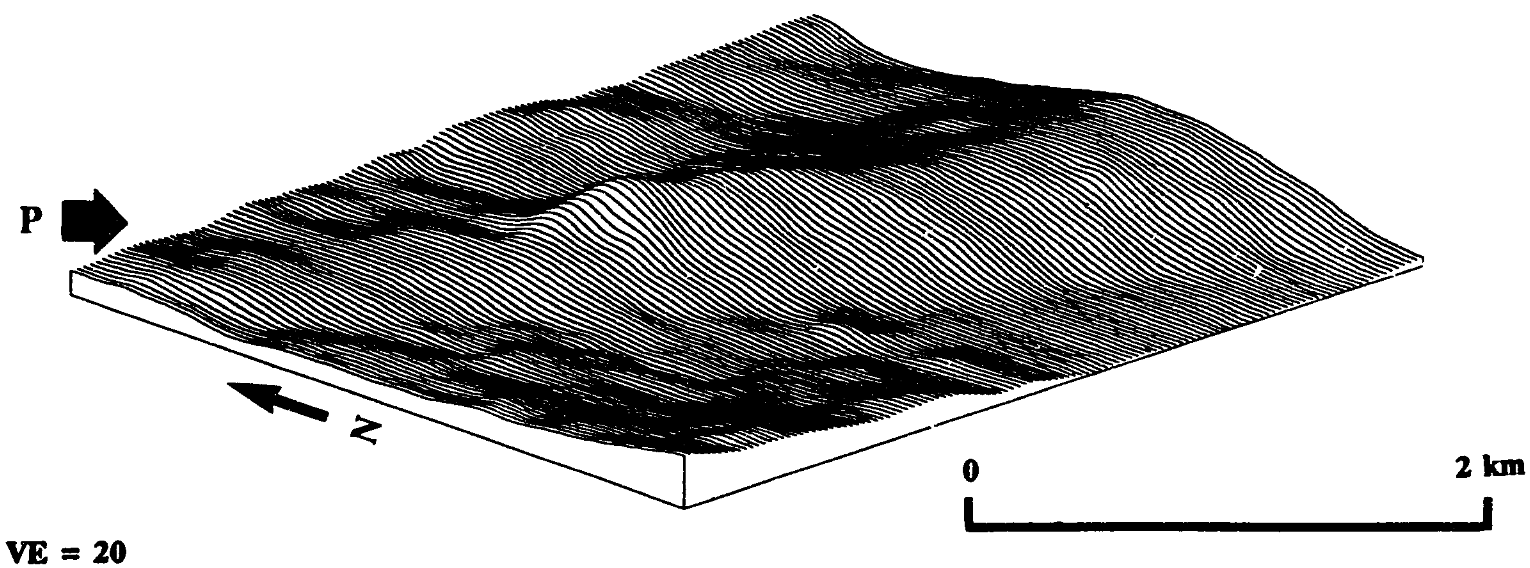


Figure 5-2: Curved residual associated with channel divergence toward Hamilton Lake (see Appendix 1). Note the undulating crestline and widening of the residual distally. Appendix 2 for compilation information.

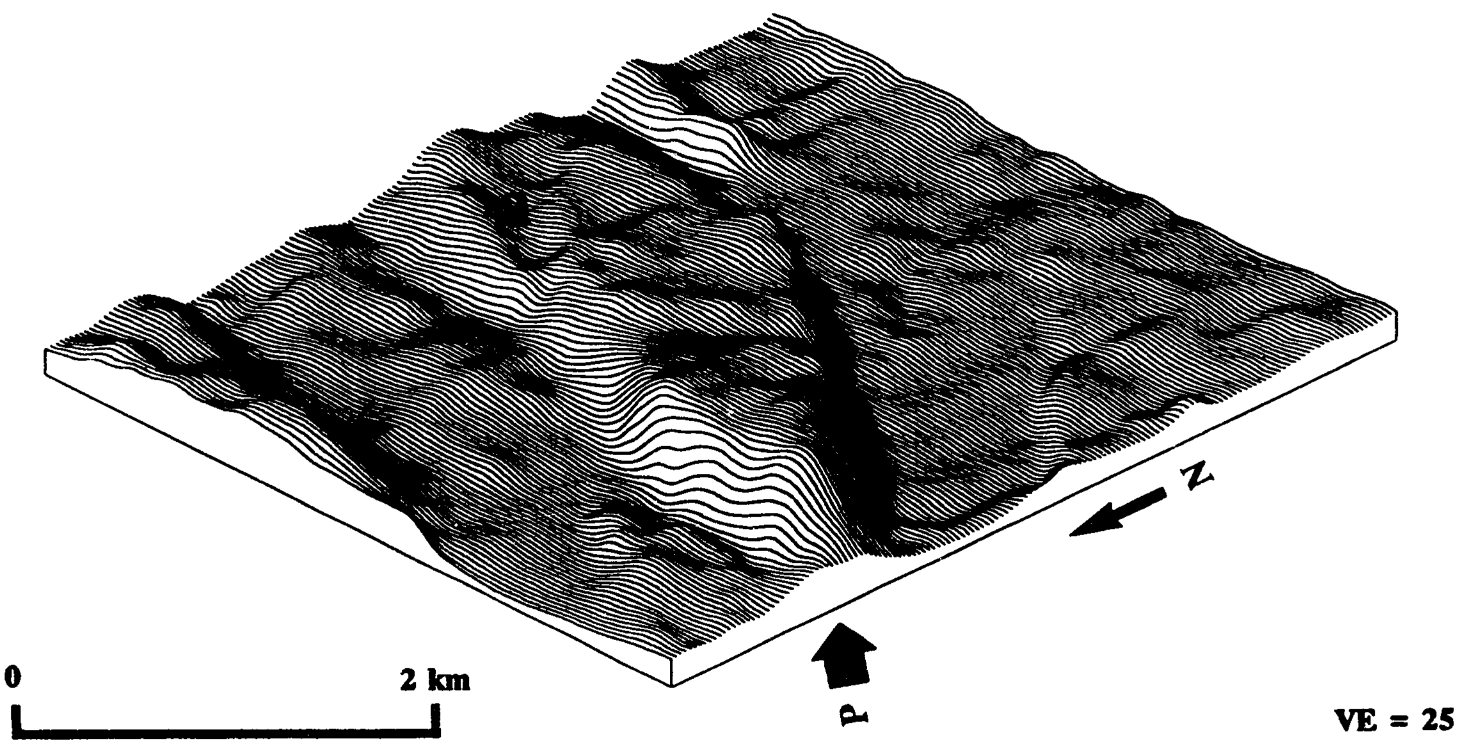


Figure 5-3: Large, curved residual with numerous residual crossings. Variability of the angle of the residual crossings produces numerous isolated peaks. A large oblique channel crossing occurs at the curve in the residual (a). Appendix 2 for compilation information.

major residuals often have multiple peaks, with intervening channelized zones. The residual crossings may be linked with residual flanking channels by gentle rises or may appear perched above the adjacent channels.

Residuals related to the diversion towards Hamilton Lake are typically narrow and long, gradually becoming less distinct as they approach the lake (Figure 5-2). Residuals are narrow at the proximal end and widen distally toward Hamilton Lake. Apart from anastomosis along the margin of this zone, these residuals are subparallel, with most of the residual crossings and superimposed forms present at the proximal end. These curved residuals are defined by channels that diverge from the eastern large-scale channel, toward Hamilton Lake. Residuals are narrow at the crest and have gently-sloping margins to the concave-up channel floor (Figures 4-6C and 5-2). Residuals at this location display residual crossings that occur where they are sharply curved. The dissection that these crossings imparts on the residual is distinct because the channels are comparatively narrow and deep. Crossings manifest themselves in obliquely-oriented channels that traverse the main residuals and form secondary "highs" oriented obliquely to both the large-scale channel and divergent residuals. The crestlines of the residuals are sharp proximally, becoming increasingly smooth down flow, with minor undulations along the crestline (Figure 5-2). Undulations along the axes of residuals are widespread in the scabland, especially where they have narrow crestlines rather than extensive upper surfaces. Isolated "knobs" that compose the undulating crestlines are separated by shallow residual crossings. Residuals oriented towards Hamilton Lake curve abruptly away from the large-scale channel, then display a decrease in curvature. It is at this abrupt transition that the most distinct residual crossings occur, whereas a gently undulatory residual crestline suggests erosion by non-channelized flows.

Where anastomosing channels delineate highly-elongated residuals, low-angle divisions and junctions of channels produced patterns where the proximal ends of many residuals are "v-shaped". The proximal slopes rise abruptly from the floors of the channels (Figure 5-4). In many cases residuals have adopted a streamlined shape, with wide residual crossings that have partially dissected the larger form into smaller residuals. Curved residual crossings, upon further dissection, impart a curved margin on smaller, superimposed residuals.

Polygonal residuals are large, with flat tops, and have marginal slopes much steeper than those associated with superimposed forms. Narrow channels dissected the terrain, creating residuals that have evolved to rectilinear margins in plan. The undulatory character of residual tops may reflect subtle channel forms or more irregular hummocks. The micro-relief on these residuals is low, usually appearing as gently rolling surfaces with small, isolated knobs. These residuals have channels, oriented along their long axes, which may display poorly developed, discontinuous anastomosis. Relatively straight channel segments are observed to dissect polygonal residuals northwest of Craig Lake, up flow of their confluence with the western large-scale channel. Some of the residuals possess a sinuous shape because the channels that delineate their margins curve toward the western large-scale channel. Polygonal residuals have sharp proximal and distal slopes, with the residual widths dictated by the low sinuosity of channel segments between the junctions defining the residuals. Polygonal residuals in the central residual zone possess "wavy" margins (Figure 5-1, h). These irregular margins are the result of the channel anastomosis in the flanking zone of smaller residuals. Channels that comprise the anastomosing reaches impinged on larger, flanking residuals as flow diversion occurred around residuals within the anastomosing reaches.

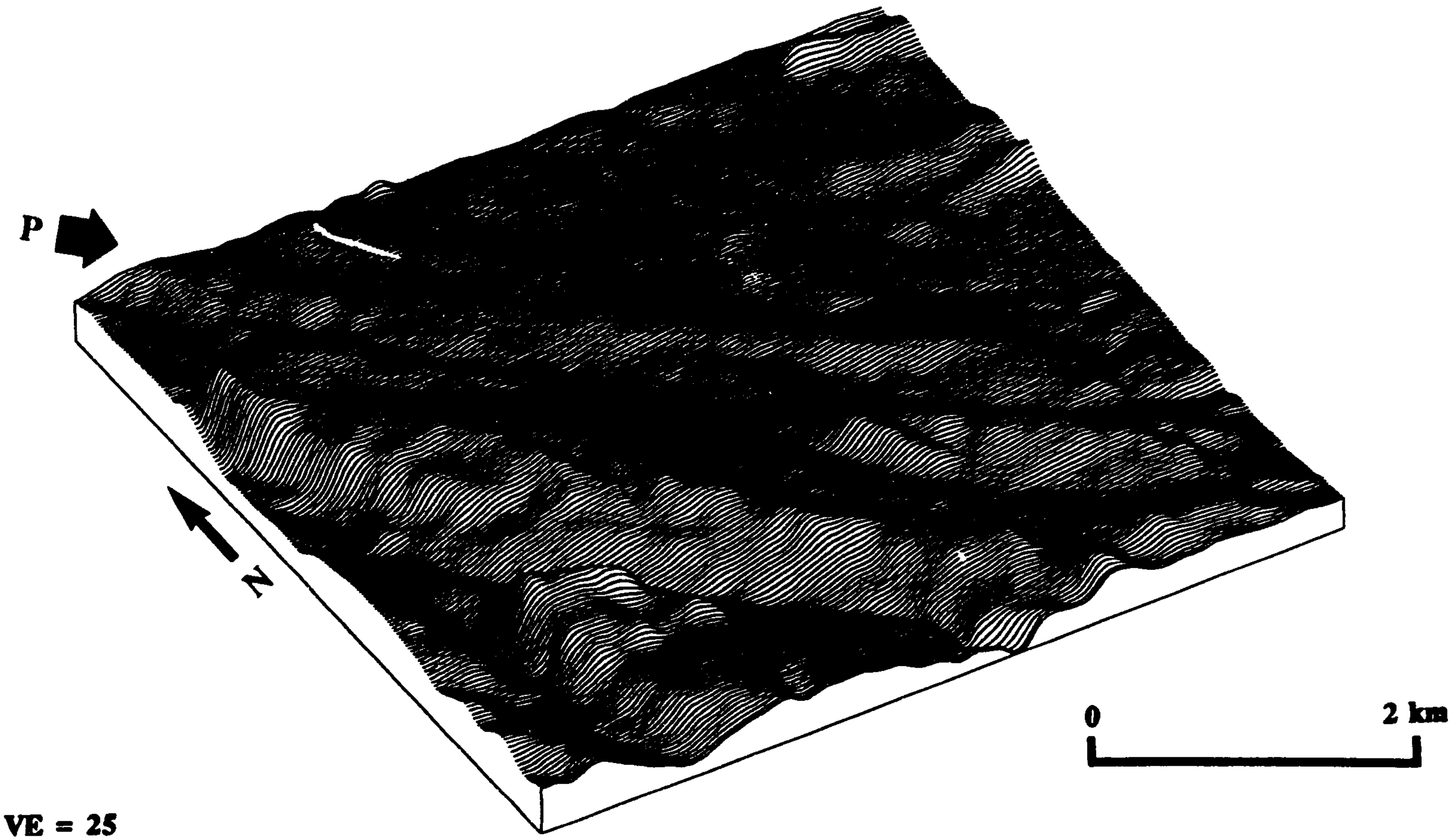


Figure 5-4: Highly elongated residuals displaying low-angle residual crossings (a) and the resulting erosional surfaces (b). Smaller residuals formed from the crossings have a high, v-shaped prow and gentle tapering of the tail. Note the elongated ridge in the adjacent channel. Appendix 2 for compilation information.

Streamlined Residuals

Streamlined residuals usually have v-shaped (Figure 5-4) or rounded (Figure 5-5) proximal ends and distally have long tapering "tails". Streamlined residuals with v-shaped prows are related to curved residuals and anastomosing channels having low-angle junctions. These characterize the margins of the western large-scale channel where eastward diversion and lateral expansion of the channel occurred. Streamlined forms are typically highest near their proximal ends and elevations decrease distally. This is readily apparent in Figures 5-4 and 5-5 where two streamlined residuals display dramatically high proximal ends, with gently sloping distal portions. Crescentic scours are absent on the proximal ends of residuals suggesting that the streamlining had occurred over the course of a single event without any flow separation. Steep along-residual slopes, down flow of the proximal "highs", are succeeded by gentle gradients along the remainder of the residuals.

These residuals are found along the western and southwestern margins of the western large-scale channel, in association with residuals left by intermediate-scale channel incision that formed anastomosing networks with low-angle channel junctions. The link between streamlined and curved residuals, defined by intermediate-scale channels, is shown by numerous troughs cut into the flanks of streamlined residuals. These troughs occur along margins of the residuals and climb up the residual flanks, to the crests, thereafter descending into the adjacent intermediate-scale channels. Similarly, along some streamlined residuals, flanking erosional benches slope upward, distally, along the length of the residuals. These erosional benches merge with the tapering "tail" of the residuals, to display erosion surfaces at different elevations. The erosion surfaces therefore often show opposed gradients along the residuals. Thus, elongated residuals

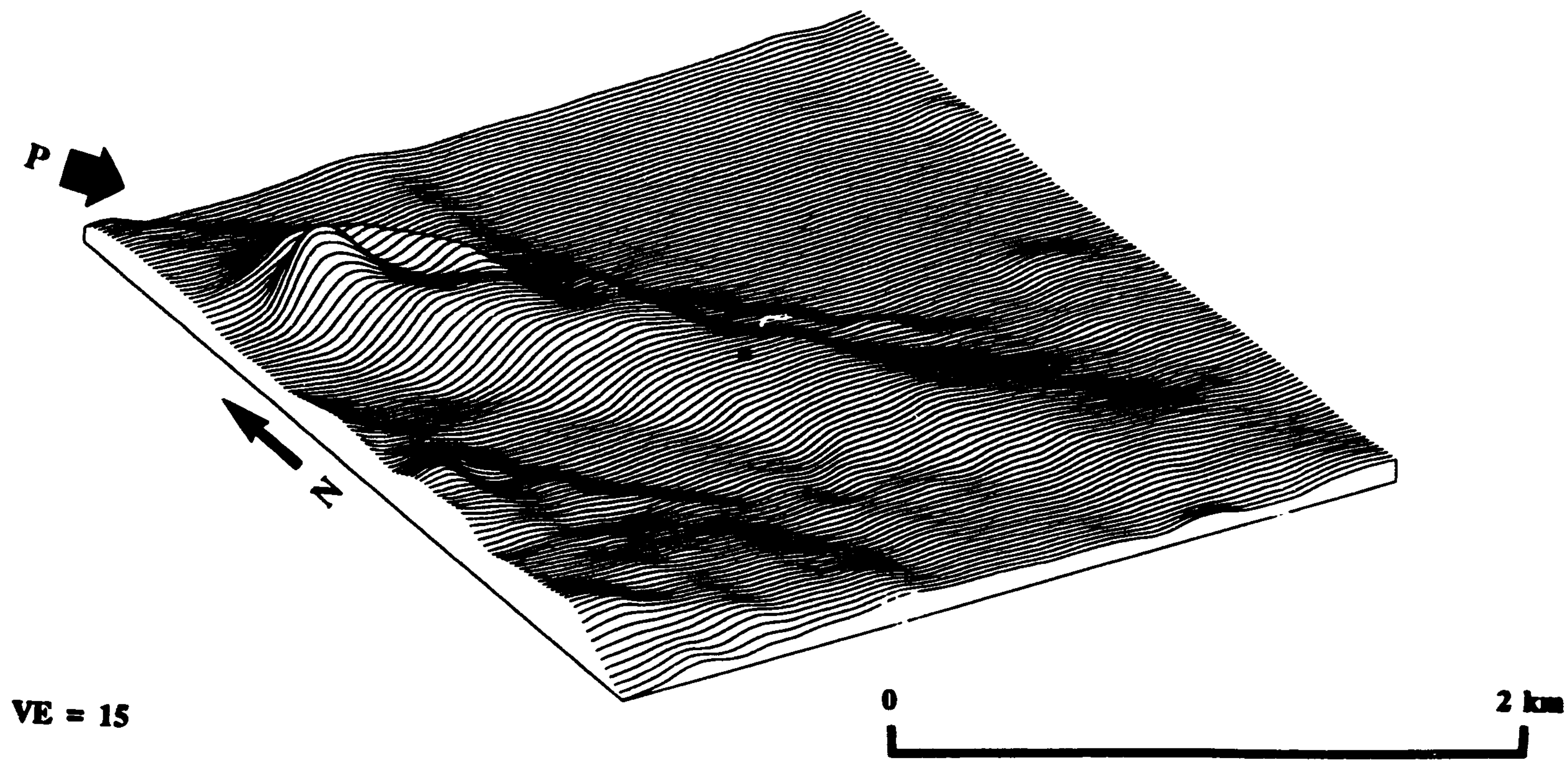


Figure 5-5: Streamlined residual located west of Craig Lake. The high proximal end gently tapers distally while displaying oblique residual crossings (a). Note dissection of the proximal end. Appendix 2 for compilation information.

take on a composite form where their flanks and tapering "tails" have smaller, superimposed erosional forms. These cross the "tails" at low angles, creating secondary forms that are less elongated than the larger residual.

Some streamlined residuals have wide, diffuse, proximal prows that taper distally. These have a wide range of sizes but smaller forms are located within wide, intermediate-scale channels along the channel margins, and assume drumlin-like shapes (see Appendix, location of Figure 6-14). Residuals in large-scale channels are generally more elongated than in the smaller channels, although distal tapering is comparable. The residual in Figure 5-5 is located along the western margin of the western large-scale channel, and is associated with the confluence of intermediate-scale channels and that large-scale channel. This residual undoubtedly had dramatic impacts on other features. Up-channel from this one, residuals associated with dissection of intermediate-scale channels extend down flow into the large-scale system. The protruding residuals, and the confluent channels, imparted a multiple-peaked proximal end and a slightly arcuate gross form to the streamlined residual.

Residual Clusters

Clusters of low-relief residuals occur in several locations and are usually composed of highly streamlined forms. These are offset, with slightly different long-axial orientations. Figures 5-6A and B illustrate offset residual clusters, indicating that partially channelized flow was conveyed between residuals, splitting and rejoining to form a localized anastomosis. A larger channel breach produced the major trough through the composite form, with smaller channels creating the residuals (Figure 5-6A). Residual clusters are usually located along the margins of large scoured areas. Figure 5-6A shows a scoured portion of the western large-scale channel, up flow from its confluence with

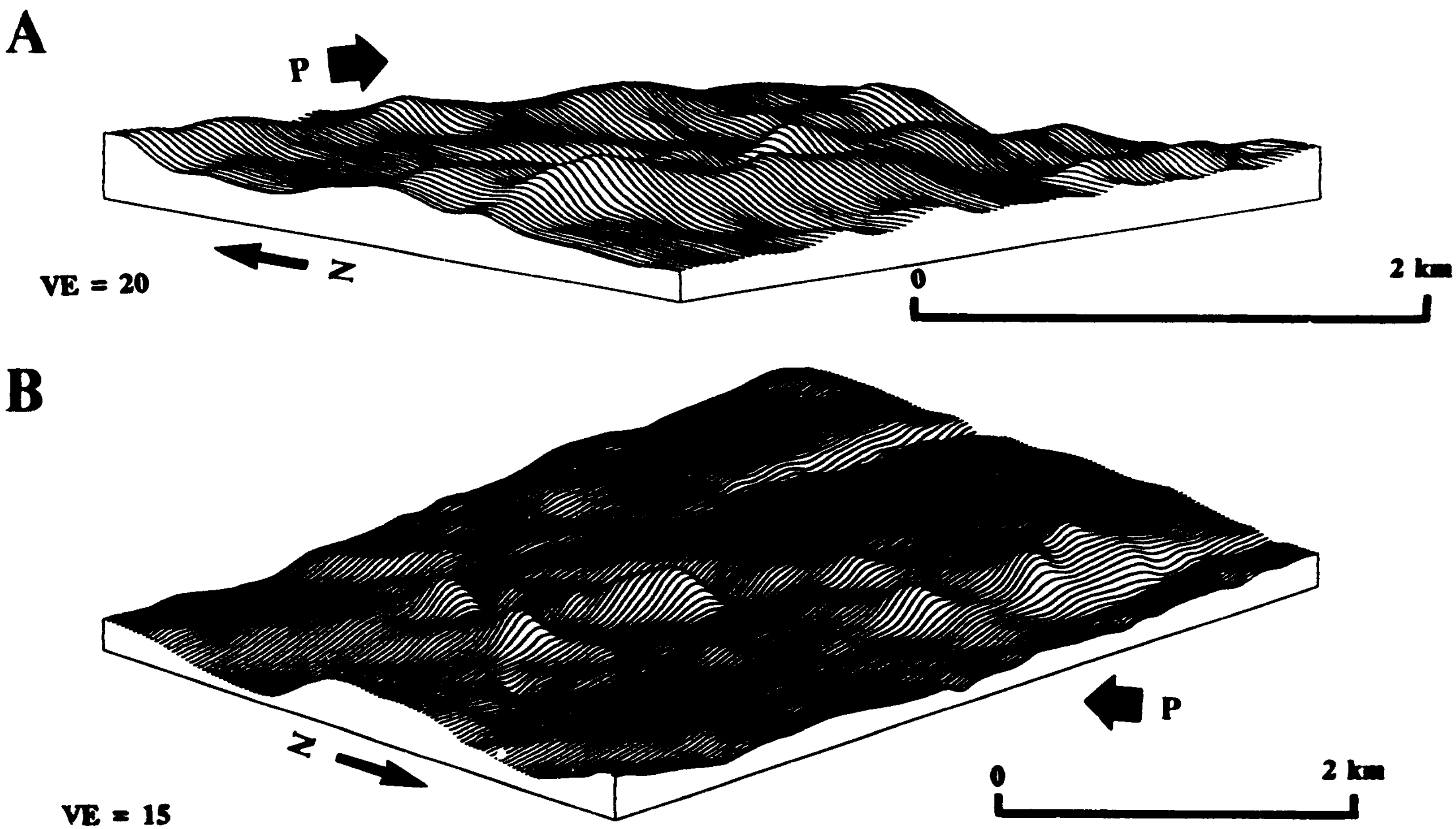


Figure 5-6: Two examples of residual clusters. A - multiple peaks and an undulating crestline associated with localized anastomosis. Note the undulatory nature of residuals in the background. B - larger drumlin-shaped residuals associated with deeper incision, smaller forms are located along the margin of a larger residual. See Appendix 1 and 2 for location and compilation information.

the eastern large-scale channel (see Appendix 1 for location). Figure 5-6B illustrates part of a large, intermediate-scale channel associated with a low-angle convergence of several channels. The juxtaposition of residual clusters and zones of enhanced erosion suggests that they represent the latest stage of glaciofluvial dissection, where submergence created localized, en echelon, patterns of streamlined residuals.

Superimposed Mesoforms

Residuals in the scabland have a variety of superimposed forms that indicate the nature of their formative environments. Two superimposed forms include: (1) transverse ridges and troughs, and (2) longitudinal and oblique troughs. Transverse ridges plus longitudinal and oblique troughs, are widespread in the scabland and are expressed by subtle undulations of the landscape. These forms are nearly indistinguishable on the ground, but vegetation differences during autumn enabled detection, from aerial photography, of numerous transverse, longitudinal and oblique elements on the larger residuals.

Transverse elements are common on large residuals in the western zone, where they are observed to be oriented transversely to the residuals' long axes (Figure 5-1). These alternating ridges and troughs are approximately equally spaced and maintain consistent orientations along individual residuals. The consistent orientation of transverse elements on a single residual does not apply when several residuals are compared. Deviations in orientation of the transverse elements are observed to be nearly 90° when residuals located in the western large-scale channel and the western residual zone are compared (Figures 5-7A and B). Though local deviations of transverse-element orientation exist, associated with individual residuals, the general orientation is roughly northeast-southwest. The orientation of these transverse elements

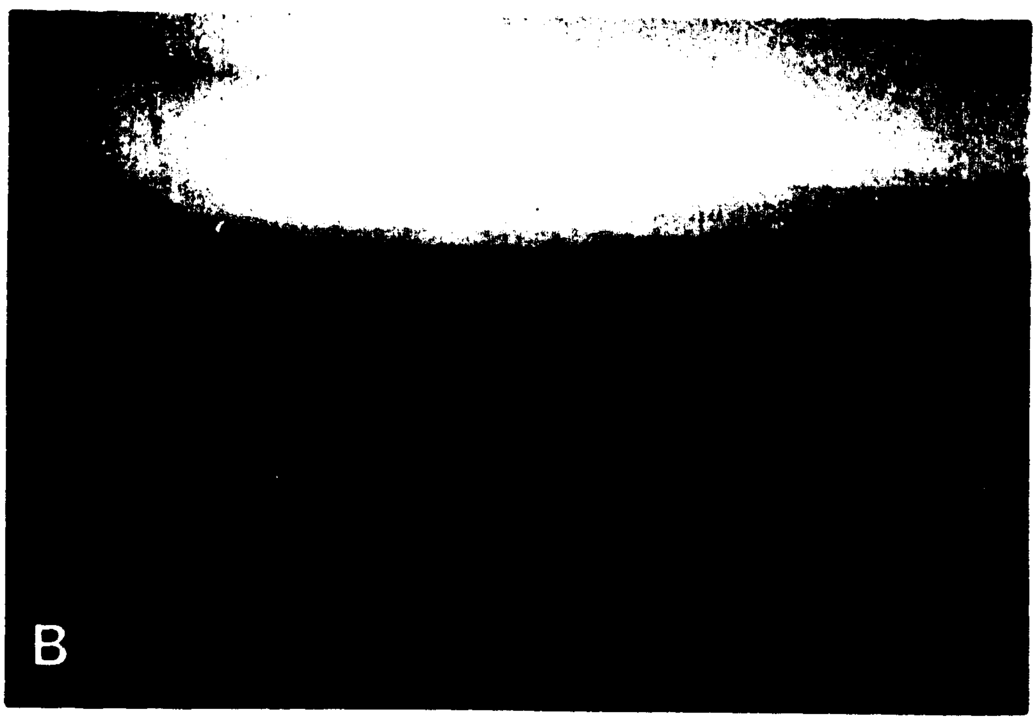


Figure 5-7: Superimposed transverse elements. A - illustrates the continuity of the forms down into the channel. B - vegetation differences enhance expression of elements along the margin and top of this residual that is defined by the intermediate-scale channel at centre. Two probable slumps located at (s).

is consistent with a general, regional, longitudinal, residual and channel northwest-southeast orientation.

Transverse ridges and troughs cover the entire upper surfaces and the margins of some residuals. Figures 5-7A and B illustrate the continuity of transverse elements down a residual margin, merging with the floor of the flanking channel. In Figure 5-7B, vegetation differences enhance expression of the subtle forms. However, as these elements merge with the channel floor they become muted and indistinct. Figure 5-7A illustrates that transverse elements superimposed on this streamlined residual are recognizable down to its base. Gullying has occurred along troughs of the transverse elements, but the modification by this erosion appears minimal insofar as the transitions between ridge crests and troughs are seldom interrupted.

Oblique troughs superimposed on residuals are generally related to residual crossings. Oblique troughs occur particularly in zones where channelized flow converged on residuals at low angles. Convergent flows resulted in oblique residual crossings that contain these troughs. Oblique troughs are roughly parallel to each other and are sometimes associated with smaller channels contained in the larger residual crossings. These troughs originate along the flanks of residuals and persist as continuous depressions along the residual crossings, disappearing where these terminate at residual margins.

SUMMARY

Residual morphology in the Coronation-Spondin scabland was largely dictated by the characteristics of the local channel forms that defined their margins. The plan shapes of residuals were largely etched by variable channel sinuosities and interconnections. Channels that display regional deflection delineate curved residuals, commonly with superimposed, shallow, broad, residual crossings that illustrate an attempt of flow to maintain a straight path. The crossings are commonly found with floor scours that are consistent with the general flow direction. Numerous residual crossings created a hierarchy of residual forms that range from large ones, up to 5 km long, to small undulations that impart a dimpled appearance, to small "highs".

The proximal ends of the residuals are either rounded or v-shaped. The different shapes of residual prows are associated with the nature of flanking channels. The V-shaped prows are products of enhanced erosion along some residual margins, whereas rounded prows are typical of isolated residuals in channels that possess relatively flat floors.

Superimposed mesoforms indicate that most residuals were submerged in the flow that formed the scabland. Transverse elements, superimposed on some residuals, are interpreted to be mainly erosional ripple forms that were cut into the residual surfaces. The absence of exposures in these subtle forms has prevented access to their internal composition. The subtle expression of these ripple elements (enhanced by vegetation differences in Figure 5-7) is consistent with the generally subtle landscape. Gently undulatory tops of residuals indicate that erosion was accomplished by sheet flows and related, shallow channels that crossed the residuals. These residual crossings were linked with the larger channels that define the residuals, and are locally indistinct. Residual crossings that exhibit deeper troughs, oriented with the flow, indicate a high energy environment and deeper submersion of the residuals during the latest stages of the formative flow.

CHAPTER SIX: SEDIMENTOLOGY

INTRODUCTION

The distribution of sediments in the channeled scabland reveals that, primarily, deposition was associated with zones that were protected from the highly erosive flows. Deposits are typically thin and are thought to directly overly bedrock in many cases. Primary depositional zones in the scabland are located along the western margin of the eastern large-scale channel where smaller channel segments, crossing the central residual zone, converge on the larger eastern channel. Apart from in this zone, deposits are scattered throughout the scabland and are mainly located downflow of large obstacles. The size of clasts found in the deposits is highly variable, ranging from large lag boulders up to 3 m in diameter, to sand that forms the matrix in many deposits.

Three main types of deposit are differentiated and described: (1) those sediments associated with residuals and forming isolated deposits in their lees; (2) deposition associated with convergent channel boundaries; the major depositional zone along the eastern large-scale channel; and (3) deposition associated with channel diversion; located at the divergence of the eastern large-scale channel toward Hamilton Lake. Three relatively minor, isolated, types of deposits will also be briefly discussed: (1) occurrences of till, (2) deposition of large bedrock boulders, and (3) small-scale glaciotectonised materials.

DEPOSITION ASSOCIATED WITH RESIDUAL FORM

SITE # 1

Geomorphic Setting

This site is located on the distal end of a large, flat-topped residual (Figure 6-1) and is associated with a complex setting of channel junctions related to the confluence of large and intermediate-scale channels. Across the channel, within which the deposit is located, a large streamlined residual separates this site from the western large-scale channel. This residual is elongated parallel with the flow direction of the western large-scale channel. Channels north-northwest of this site show divergent flow patterns with one segment oriented southwards, intercepting the site location. A larger intermediate-scale channel determines the residual margin to the north, and the margin of deposition on the eastern side. Superimposed on the large, flat-topped residual are subtle channels that display some anastomosis, and transverse ripple forms are located along the southern portion of the residual. An indistinct trough, that roughly parallels the main channel, extends between the main deposit and the residual.

Site Description

The bar surface is characterized by numerous, lobate undulations and lower troughs that diverge from the main trough. The lobate forms display large clasts along their distal end, indicating that the form is probably 1 to 2 clasts thick. These superimposed forms are offset from one another at regular intervals and occupy higher portions of the bar surface, adjacent to the troughs. Internally, the bar is characterized by highly variable sediment size, sorting and grading. Sediment size ranges from boulders (up to 1 m in diameter) to sand. Generally, sediment size tends to decrease southward, although sand is present throughout, providing a supporting matrix for the

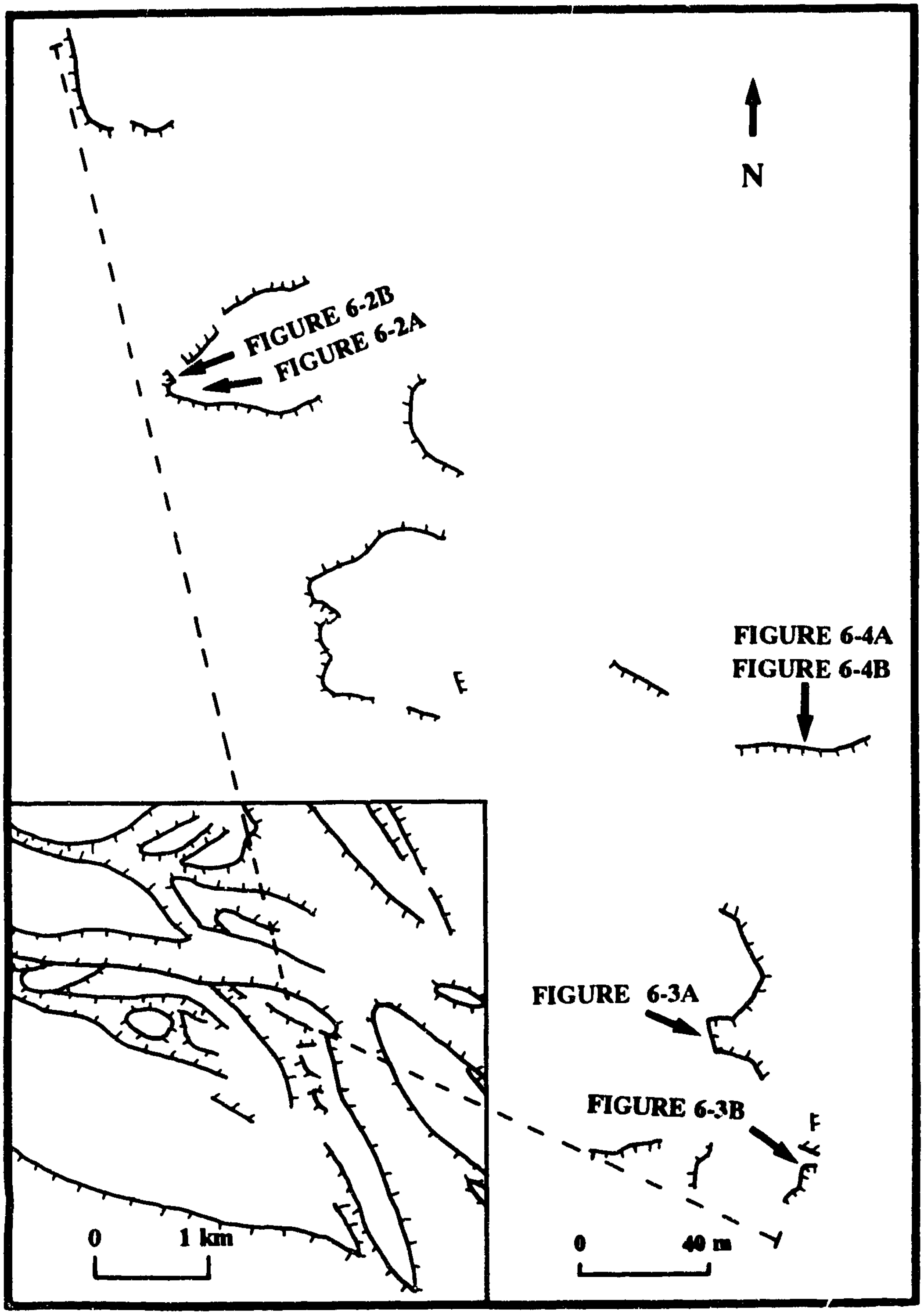


Figure 6-1: Location of Site #1 and the associated geomorphic features (inset). Locations of Figures 6-2, 6-3 and 6-4 are shown in the enlarged portion. Appendix 1 for location.

larger fractions.

Figures 6-2A and B illustrate the variable sediment rock types and also the polymodal textural character of the sediment. The boulders are imbricately clustered while the finer sediment that provides the support for these imbricate clusters does not display any structure (Figure 6-2B). These smaller fractions have chaotic orientation where vertical alignment of clasts is common. Boulders tend to occur in clusters (Figure 6-2A) where they are stacked on each other and are separated by intervening zones of chaotic sediment. Chaotic sediment commonly contains local bedrock clasts (Figure 6-2B, a) that may be rounded to angular, with a wide range of size.

Figure 6-3 illustrates the variability of the contact between gravels and the overlying aeolian sands. Figure 6-3A shows a large trough along the right side of the face where the sediment is primarily gravel, with little matrix material. This portion is fairly well sorted and is underlain by a unit of conspicuously larger clasts (a). Conversely, the left side of this trough is composed of larger clasts that have significantly more matrix material and are not as well sorted. Figure 6-3B shows a sand lens that is bounded by much coarser material. The dip of the clasts is into the face and slightly to the right. There appears to be no noticeable gradation within the finer lens, although some large clasts are found within this finer unit.

Figure 6-4A illustrates the indistinct delta-like foresets located along the eastern margin of the site. These avalanche faces are approximately 4 m in height and dip toward the east. A variable dip angle of these avalanche faces is associated with a change in grain size. Individual faces may be matrix-rich to nearly devoid of matrix. Individual faces are composed of gravel and sands and commonly have isolated boulders interspersed. There is a noticeable clustering of similar-sized clasts along individual

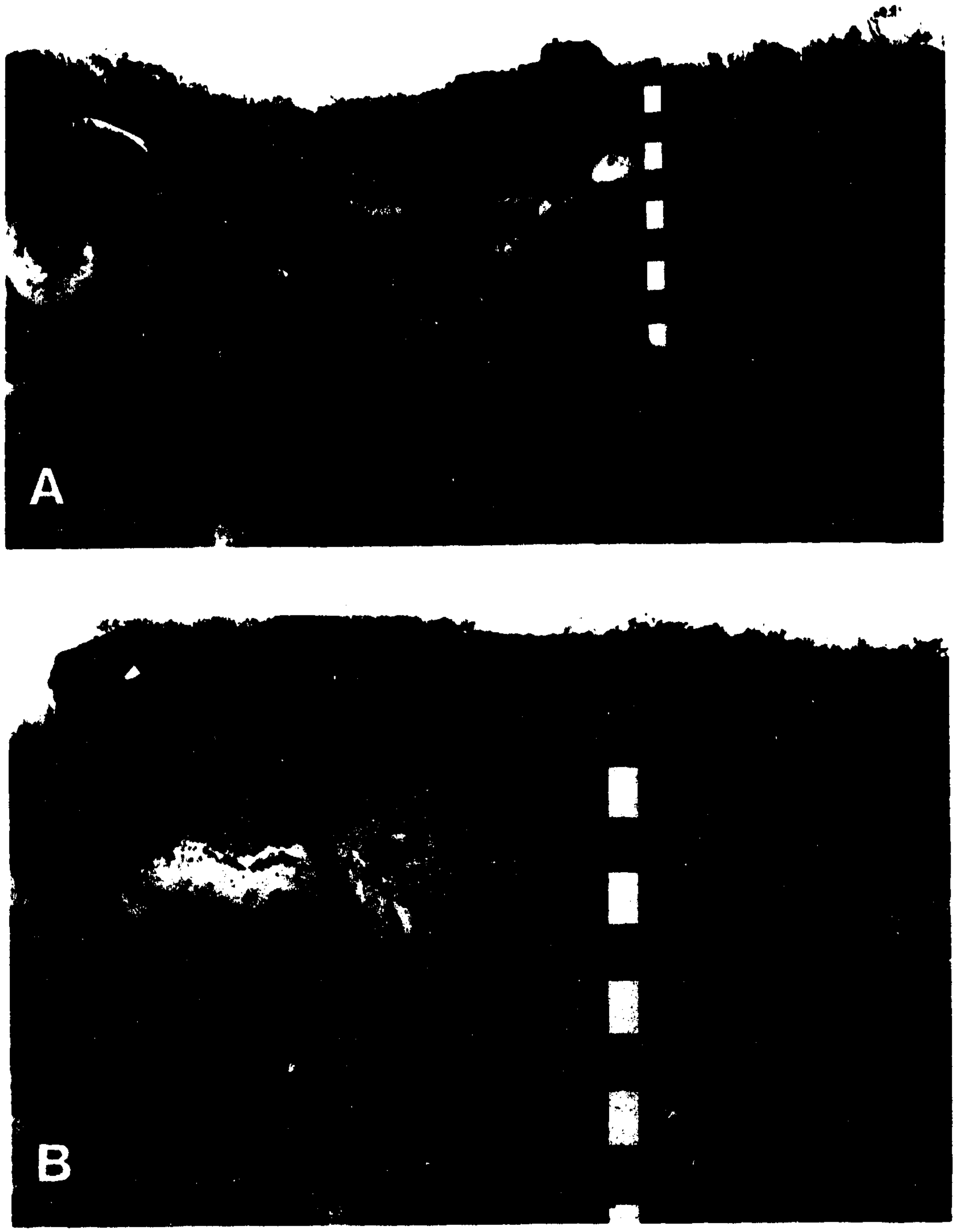


Figure 6-2: A - Imbricate boulder cluster (located to the left of the metre stick) suspended in a heterogeneous mixture of chaotic sediment. B - Imbricate boulder cluster and chaotic sediment including local bedrock clasts (a). Metre stick for scale.

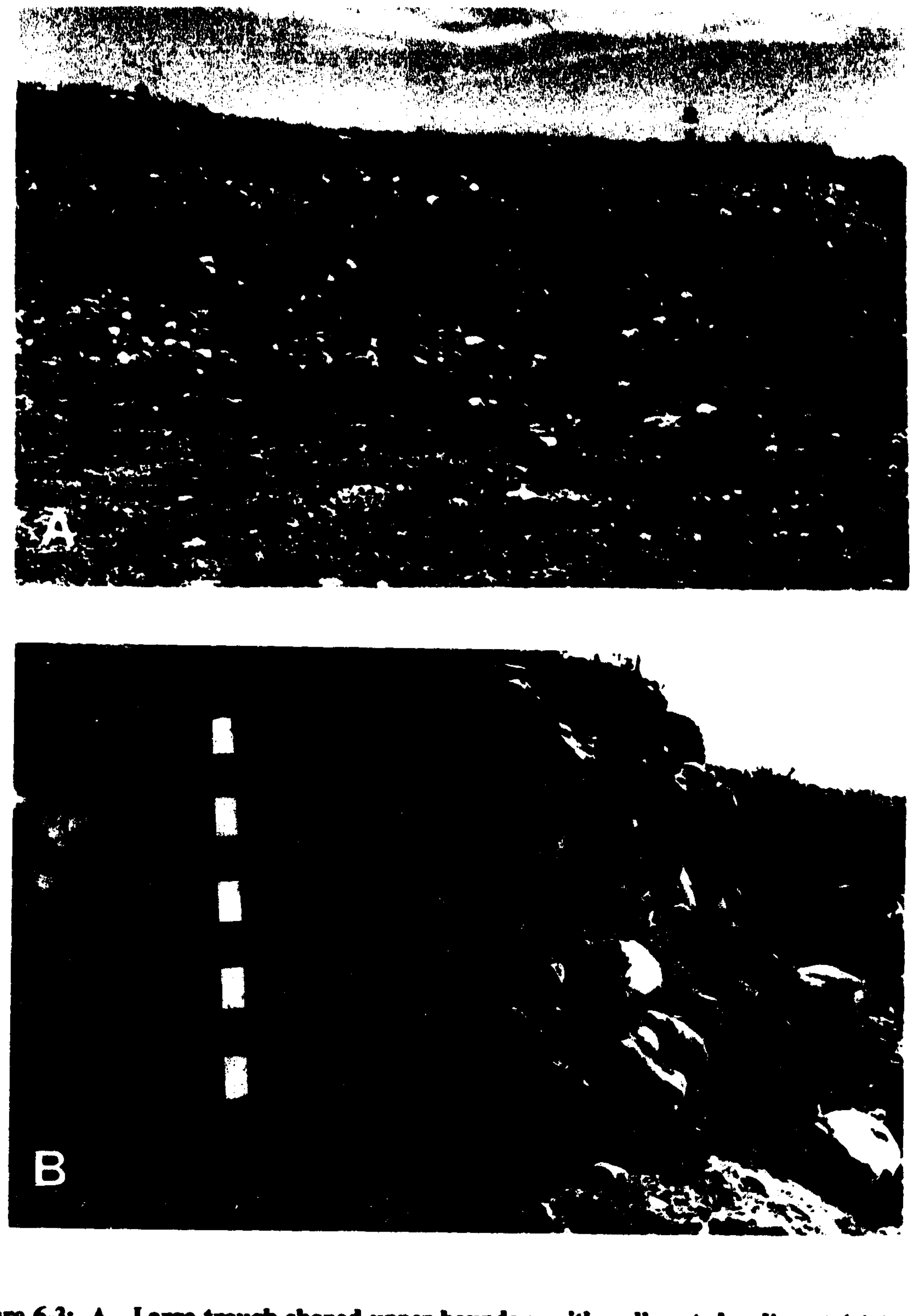


Figure 6-3: A - Large trough-shaped upper boundary with well sorted sediment (a) to the right. B - Sand lens associated with clasts dipping away from the viewer. Metre stick for scale.

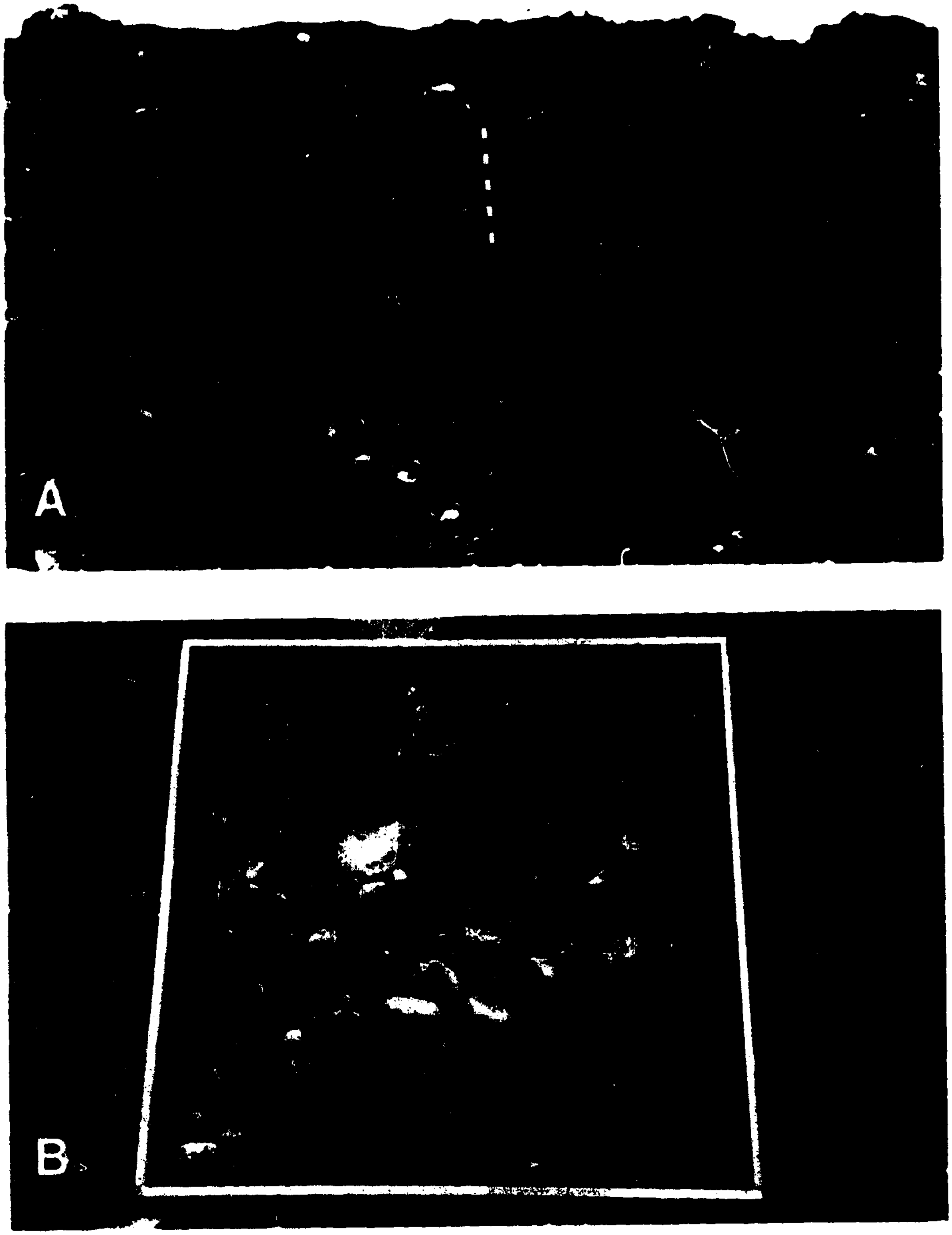


Figure 6-4: A - Large avalanche faces displaying different degrees of dip and sorting. Note that the faces with higher dip angles are associated with larger clasts (metre stick for scale). B - Close-up of one avalanche face illustrating the imbrication of clasts that can occur (metre grid for scale).

faces where clasts may be clast supported (Figure 6-4B). The amount of matrix present decreases, and the size of the clasts increases, where the angle of the avalanche faces increases. Interspersed within this bedding are numerous coal fragments and sandstone clasts. At the top of these faces there is a planar bedded unit, about 1-2 clasts thick, that contains imbricate clasts.

Interpretation

This site represents pendant bar deposition that occurred downflow of a residual. Deposition of this pendant bar was complicated by the influence of channels that converged on it. The channel from the north appears to be linked with the trough that formed along the end of the residual. The bifurcation of this trough has created multiple smaller troughs that trend toward the main channel into which the bar is deposited. The bifurcation of this trough is believed to have been associated with interference, created as flow longitudinally crossing the residual encountered this site. The entire residual was inundated at the time of deposition of this pendant bar. This is attested to by the presence of anastomosing channel segments and transverse ripple forms that converge on the pendant bar.

Sediments in the bar indicate high flow velocities, producing bedforms that migrated across the surface, contributing to the avalanche faces, and thus building the bar progressively eastward. Imbricated clasts, in conjunction with the finer sands, indicate that bedload and suspended sediment were important in building the bar. The chaotic nature of the finer sediment between the large imbricate boulders suggests a hyperconcentrated flow. The imbrication within individual avalanche faces suggests that failures occurred within the material; the clasts became imbricate as material slid down the face. The clustering of imbricate boulders on the surface of the bar, forming linguoid bedforms with larger boulders located along the '' 'al ends, represents variable gravel migration across the bar surface. Trough forms cate that the bedforms superimposed on the bar were of low relief.

Avalanche faces with different dip angles, and highly variable sediment size and sorting, suggest that longitudinal sorting was important. Clustering of imbricate boulders suggests that one possible mechanism for sorting material on these avalanche faces could have been the destabilization of cluster bedforms. In this scenario, large clasts become stationary and other clasts pile up on the proximal end; a saltating clast striking the cluster may remobilize the whole bedform (T. Brennand, pers. comm. 1992). These cluster bedforms may explain the surficial character, in addition to characteristics within the sedimentary sequence.

SITE # 2

Geomorphic Setting

Large gravel deposits are found perched on the top of residuals above channels that form the anastomosing networks. Figure 6-5 shows the location of one of these large perched gravel deposits. This deposit is found on a large residual that forms the divide between channels that contributed to formation of the western and eastern large-scale channels. This deposit is situated in the lee of a slightly higher proximal end of the residual and upflow from numerous channel forms, superimposed on the residual, that indicate flow to the northeast (Figure 6-5). Till exposed in a road cut at (a) (Figure 6-5, inset) occurs at elevations that equal the elevation of the deposit.

Site Description

This site is characterized by a complex assemblage of cross-stratified units that

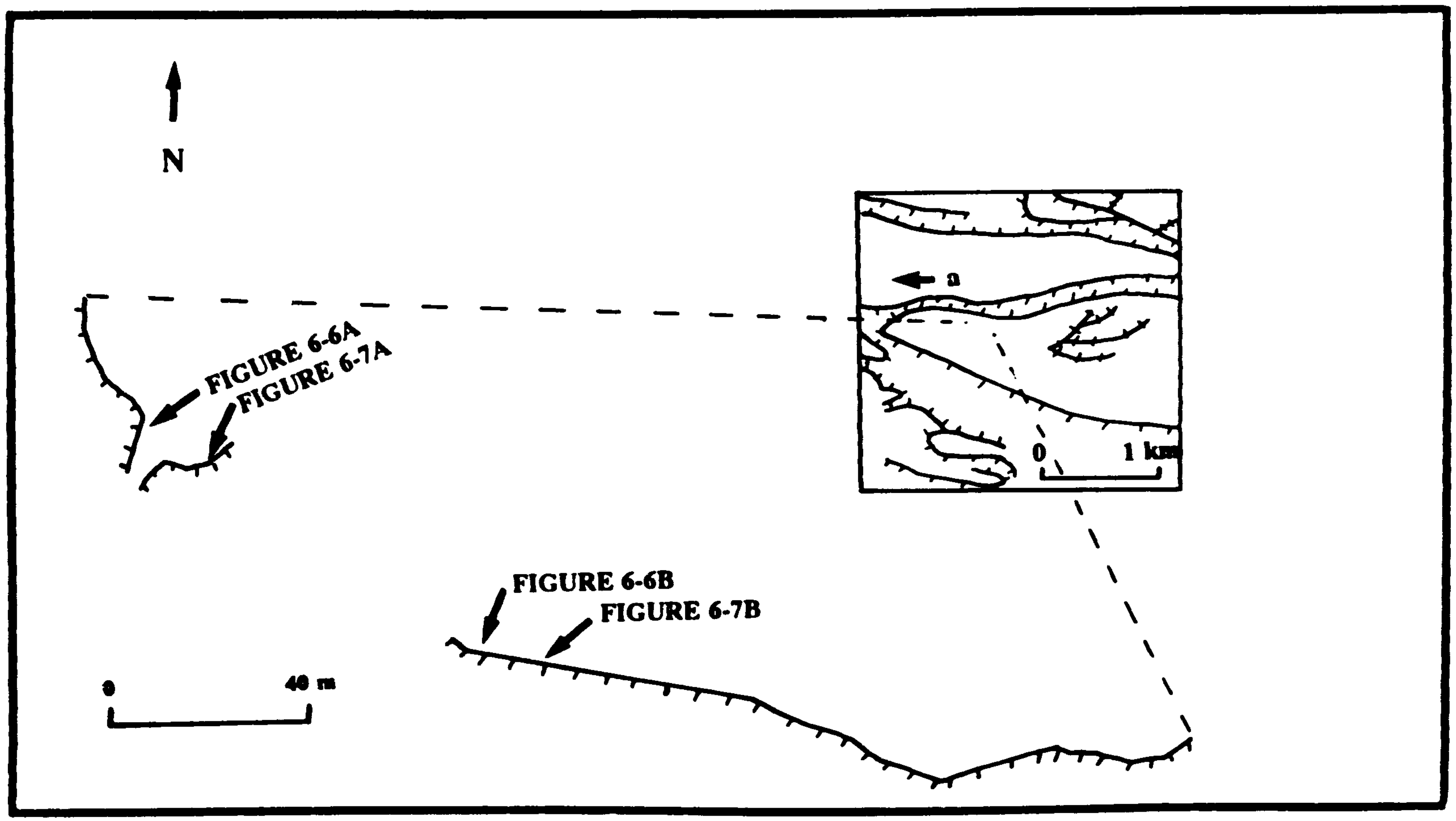


Figure 6-5: Location of Site # 2 on top of a large residual, and the adjacent location of a till exposure (a). This residual forms part of the regional flow separation that forms the western and eastern large-scale channels. Superimposed on this residual are numerous channel forms that indicate flow diversion toward the northeast.

contain significant amounts of coal. This makes individual beds easily distinguishable. Figure 6-6A illustrates the large amount of coal present in the units and contains a conspicuous local bedrock clast (a). Figure 6-6B illustrates the cross-stratification roughly parallel to flow, with one side of a trough shown at (a). Bimodal gravel and sand are exposed at the bottom of the section (b) in addition to some sediment packages that do not appear to have any structure (c). Figure 6-7A illustrates the cross-stratification as it appears immediately downflow from the Figure 6-6A location, where well defined trough cross-bedding, with sorted sediment, changes to larger troughs with polymodal sediment. There are also numerous occurrences of till blocks included in the sediment (Figure 6-7B). Approximate paleocurrent estimations indicate flow generally parallel to the overall residual form, although there are diversions from this, indicated by abrupt changes in angle of crossbedding and sediment sorting.

Interpretation

Water that deposited the cross-bedded gravels and sands generally flowed along the axis of the residual or at an oblique angle to it. The deposit occurring on the downflow side of an obstruction, located at the proximal end of the residual, and small channels oriented towards the northeast, attest to flow diversion from the large scoured zone to the south, over the residual and contributing to flow on the north side of the residual. The facts that diamicton and glaciofluvial deposits occur at similar elevations, in addition to occurrences of diamicton and coal from the local bedrock, suggest that deposition must have occurred while erosion of till and bedrock, upflow, was also occurring. Given the likely initial thickness of till in the area, the deposit found on the top of this residual must have been inundated with flowing water when bedrock in the adjacent channel was being eroded. The flow that deposited sediments at Site # 2 must

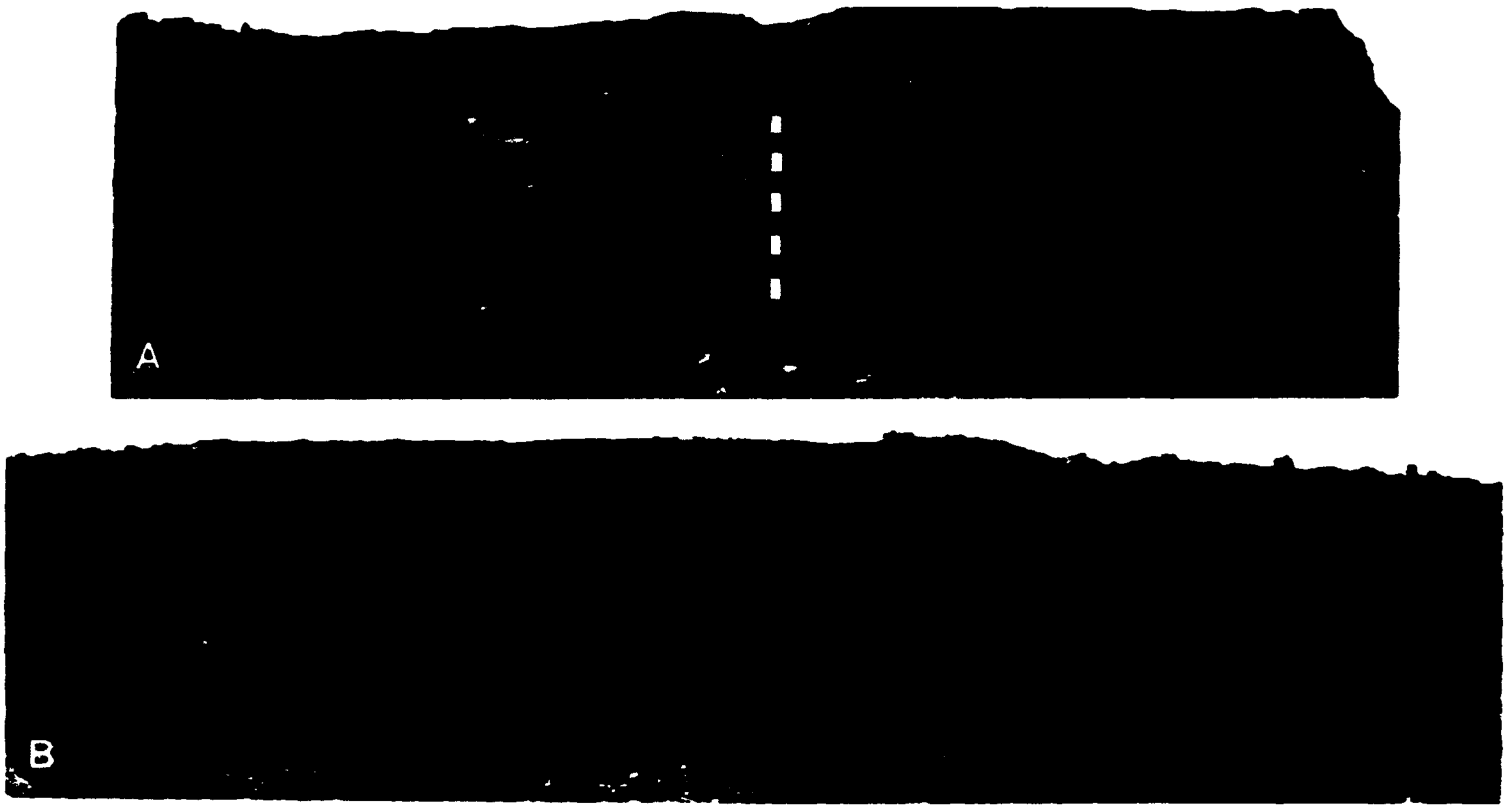


Figure 6-6: A - Large-scale cross-bedding accentuated by the presence of large coal fragments. Local bedrock clasts are also present (a). B - Trough cross-bedding with (a) being nearly perpendicular to flow, bimodal gravel at (b) and structureless sediment (c). Metre stick for scale.

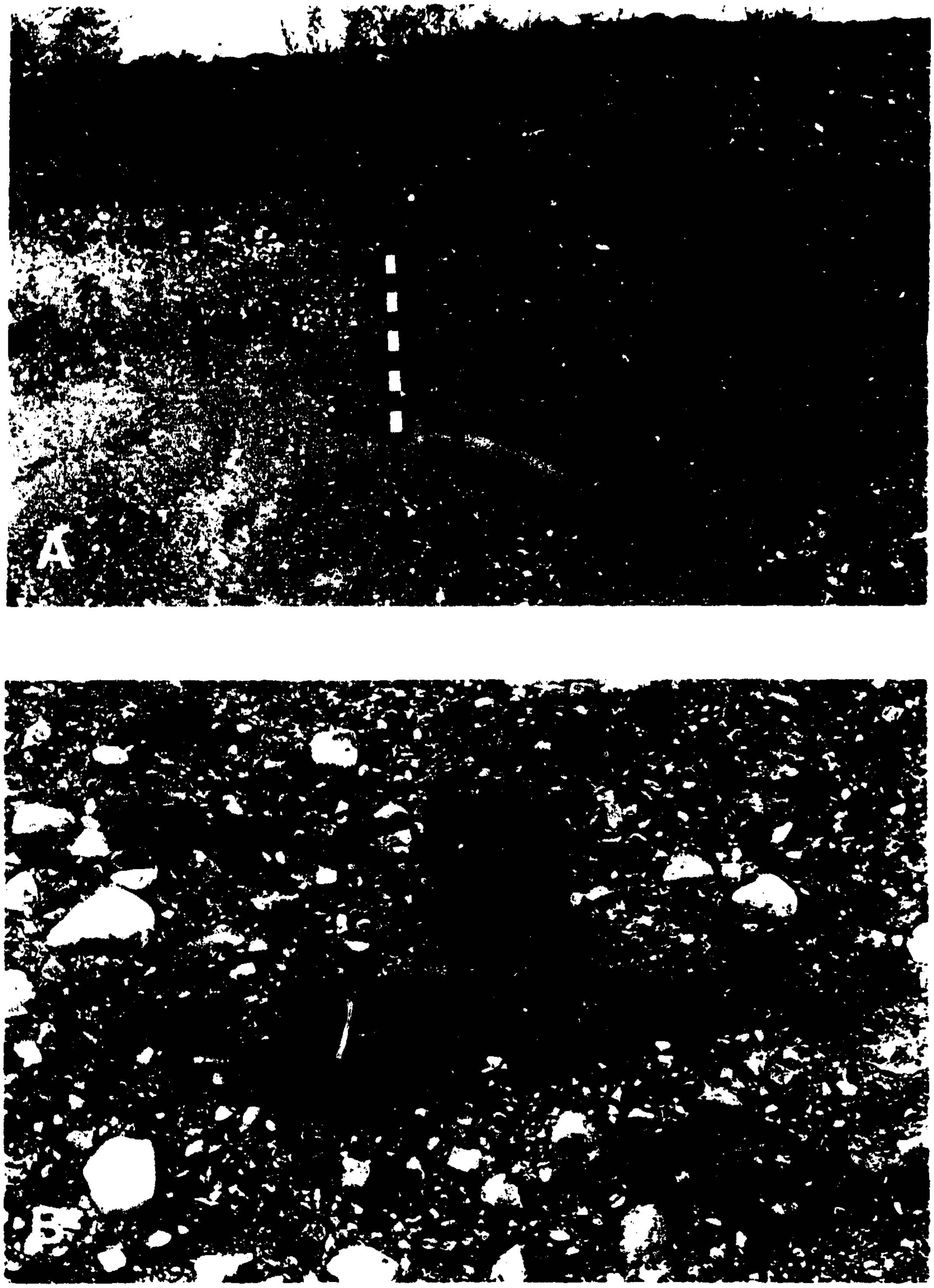


Figure 6-7: A - Trough cross-bedding showing an upward transition to larger sediment, larger troughs and a lower degree of sorting (metre stick for scale). B - A small till inclusion.

have eroded material from the local bedrock, but the deposit is perched ~ 25 m above the adjacent channel. This would suggest that there was an extensive till cover prior to the event that formed the channels and deposits that characterize Site #2.

DEPOSITION ASSOCIATED WITH CONVERGENT BOUNDARIES

SITE # 3

Geomorphic Setting

This site is located along the convergence zone between the eastern large-scale channel and diverted portions of the western large-scale channel that form the elongated residuals. The western lateral furrow of the eastern large-scale channel has diverted around the depositional area that contains this site. Channels that form elongated residuals, associated with the western large-scale channel diversion, become muted at this point and an irregular, amorphous zone dominates (Figure 6-8). This site is located on a long ridge flanked by two troughs.

Site Description

Figure 6-9A shows part of the pit excavated into the crest of one west-east trending ridge. It illustrates the southern flank of this ridge where low-angle slopes dip to the south. There are several sets of normally graded sediments within this section (a) where cobbles grade into sand. Abundant coal in the section helps to delineate some of the beds. At (b) an erosional surface shows beds dipping to the south, truncating some that dip to the north. This erosional surface is demarcated by larger clasts. Figure 6-9B displays some sorting, and several distinct stone lines have trough shapes (a). Indistinct normal grading separates these stone lines, that appear similar to those in Figure 6-9A (although the thickness of each bed is less). Along the left margin of Figure 6-9B the

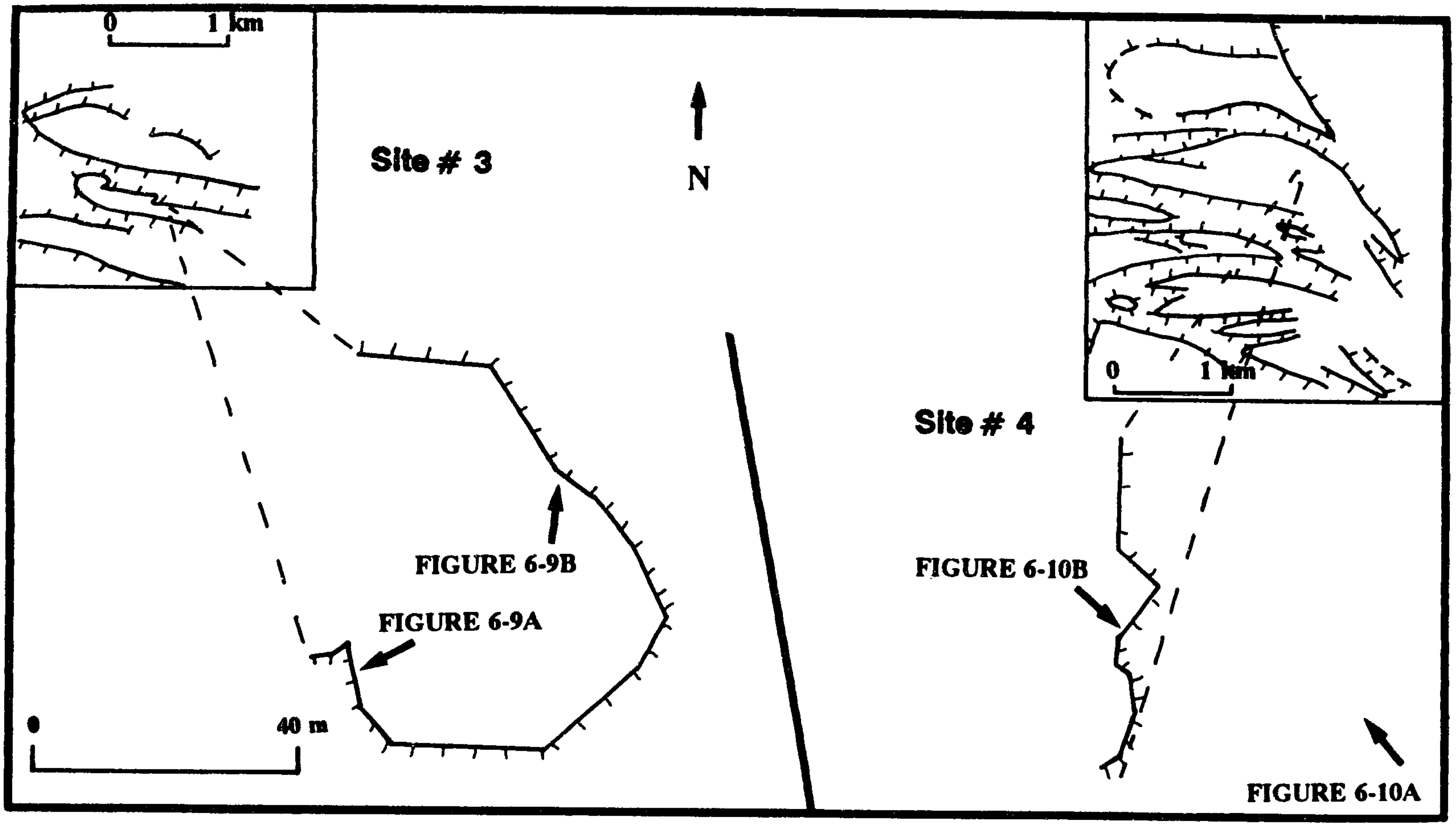


Figure 6-8: Location of Sites # 3 and # 4. Depostional features that typify the western margin of the eastern large-scale channel.

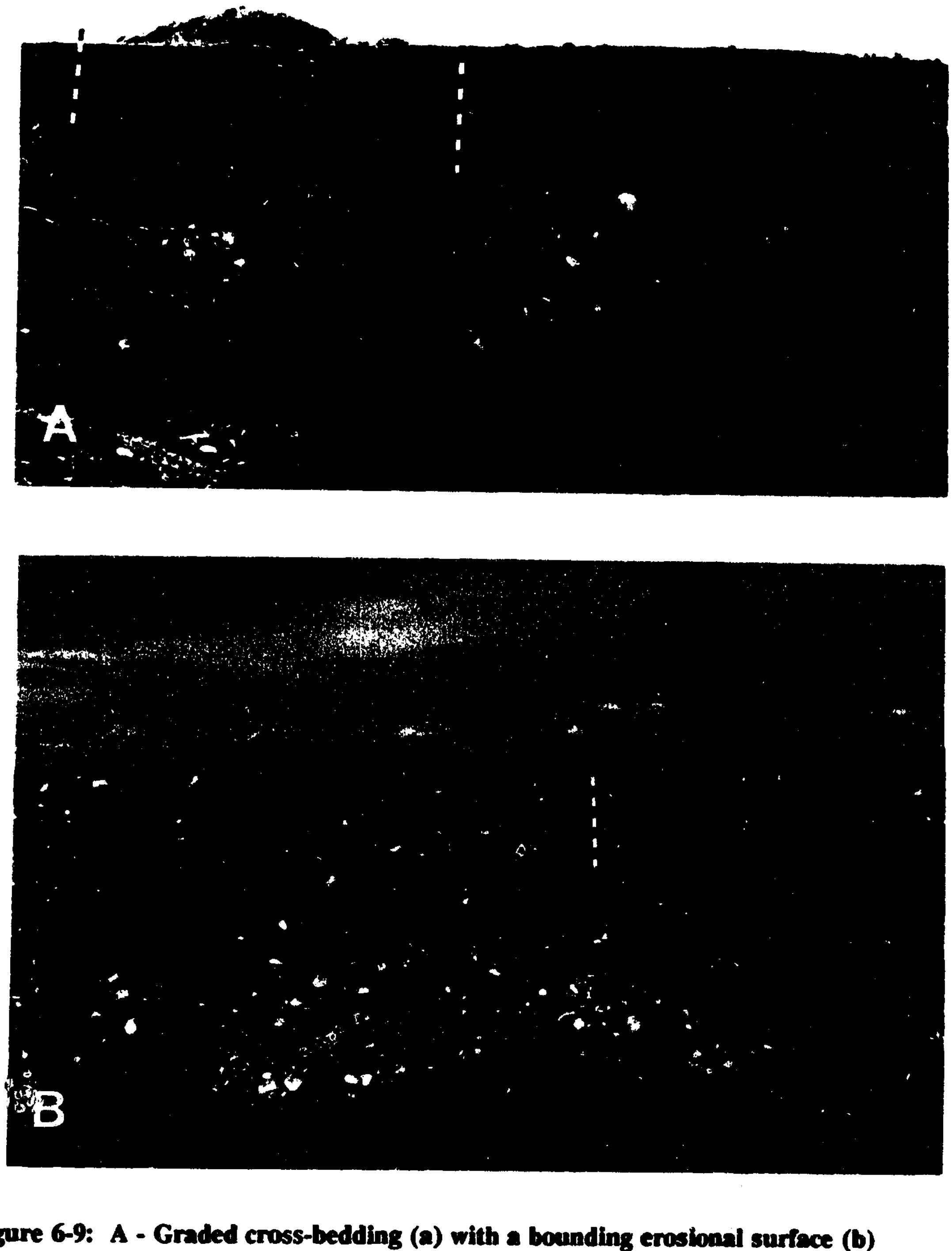


Figure 6-9: A - Graded cross-bedding (a) with a bounding erosional surface (b) indicating change in local flow direction. B - Intersecting trough-shaped stonelines (a). Metre stick for scale.

beds form indistinct troughs and appear truncated by the trough-shaped stonelines that are prominent in the centre of the picture.

Interpretation

This site represents a large dune form, associated with the sediment influx from channels that converge on the eastern large-scale channel. The dipping beds in Figure 6-9A represent the lee side of this dune, whereas Figure 6-9B represents troughs associated with scour along the crestline. Alternating scour, along the stoss and crest of the bedform, combined with pulses of sediment, could have formed the stone lines. Grading, apparent in the bedding, reflects fluctuating sediment transport rates that may have been pulsatory. Alternatively, the bedforms may have acted as temporary storage reservoirs, episodically releasing sediment. Truncation of some beds, as in Figure 6-9A, suggests lateral and/or longitudinal migration of bedforms. In this case the distal end of one bedform truncates the proximal end of another.

Disgorgement of sediment from the constricted channels resulted in deposition of sediment as the flow expanded. Depositional bedforms reflect interference patterns that created a chaotic terrain. The high-angle convergence of these two channel systems resulted in an assemblage of bedforms displaying orientations that reflect the flow direction within the large-scale channel.

SITE # 4

Geomorphic Setting

This site is located in the convergence zone of channels that dissect the central residual zone and the eastern large-scale channel. At this point, channels arc towards the large-scale channel (Figure 6-8). This site is at the margin of a subtle channel form

.that displays a series of elongate ridges and swales. This site consists of a large shallow pit, cut transverse to flow direction in a large mound, and two adjacent ridges of gravel. This mound is rounded on the distal end and excavation has removed the proximal end. Distal slopes are gentle as they merge with a trough found between two elongate ridges that display smaller, transverse elements superimposed on them (Figure 6-10A).

Site Description

This site is characterized by high-angle cross-bedding that intersects adjacent sets at high angles. Sorted sand lenses are present and form part of the core of the feature in Figure 6-10A. This sand core is truncated by gravels, whose beds dip at a high angle. Elsewhere (Figure 6-10B) there appears to be a gradual transition between cross-beds with high proportions of sand, and those composed primarily of gravel. The intersection of different cross-bedded units appears to coincide with topographically low troughs on the surface. As with many other sections in the area small clasts of local bedrock, including coal, are present.

Interpretation

This site represents migrating bedforms, formed as flow crossed the central residual zone and transported material out into the flow of the eastern large-scale channel. Lateral expansion of these channels resulted in the contribution of sediment from a number of point sources, creating interference. Elongate ridges display small, superimposed, ripple forms and the troughs represent areas of deeper water and more intense flows. The orientations of the channels and bedforms indicate an influence of flow conveyed in the large-scale channel. This site suggests that flows, heavily laden with sediment eroded from the central residual zone, encountered the large-scale channel and deposited part of this load in extensive deposits along the western margin of the

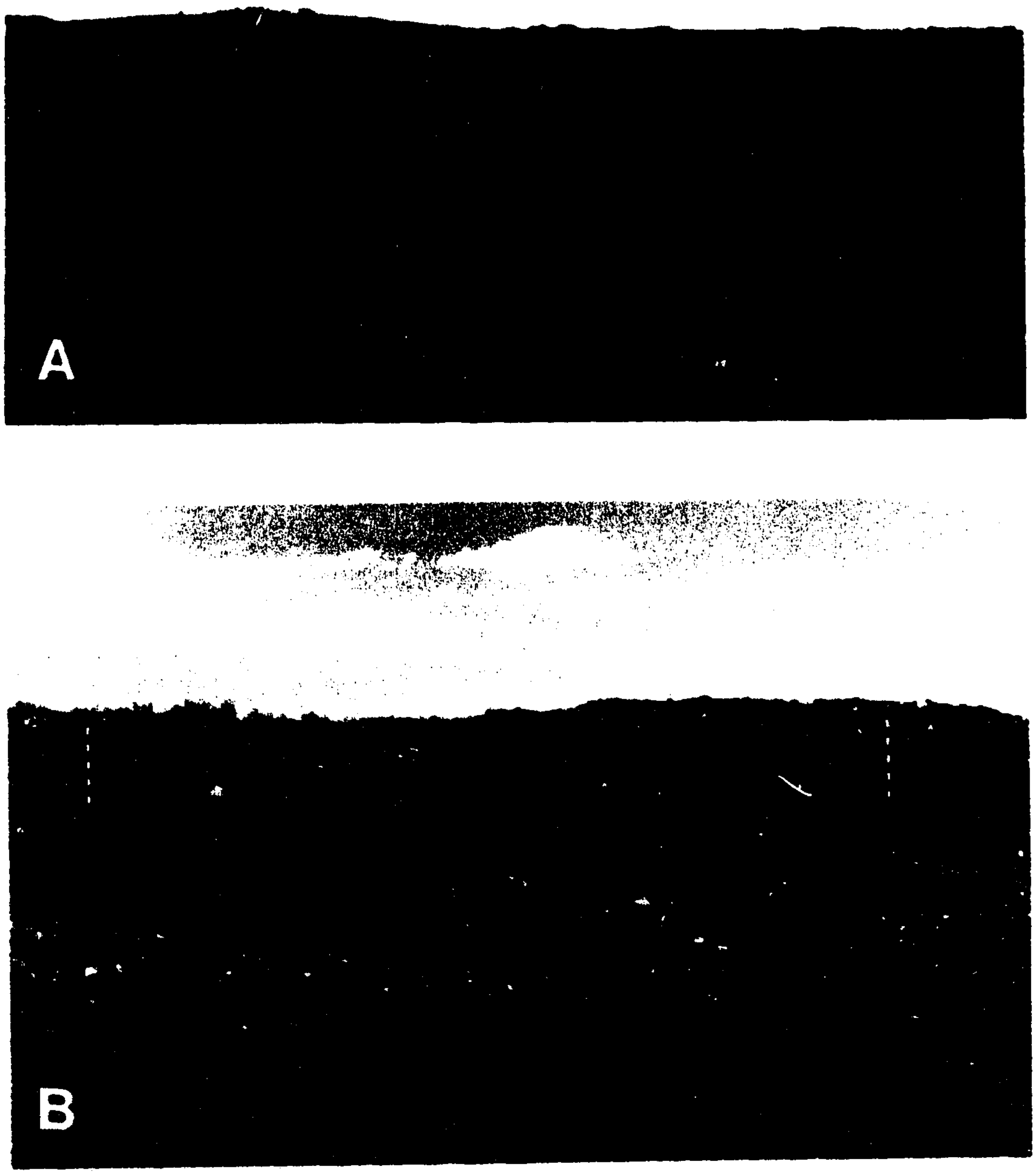


Figure 6-10: A - Lobate bedform associated with a long trough (to the right). B - Internal structure of the bedform showing steeply dipping gravel beds that contain sand. Metre stick for scale.

large-scale channel.

DEPOSITION ASSOCIATED WITH CHANNEL DIVERSION

SITE # 5

Geomorphic Setting

This site is located down-channel from the channel diversion that occurs from the eastern large-scale channel toward Hamilton Lake (Appendix 1). In this area channels are indistinct as residuals become broad and low, fading out along the margin of Hamilton Lake. This location is characterized by shallow channels and transverse elements that form long, arcuate, ridges and troughs. These are concave down-channel. Figure 6-11A is a view obliquely up-channel, about 100 m west of the Figure 6-11B site.

Site Description

The sediments found in this area are typically cross-bedded sands and gravels. These sediments may display a bimodal texture, as in Figure 6-11B, or be well sorted. The clast dips are consistent with the contact between gravels and the overlying aeolian sands (Figure 6-11B). The gray material forming a wedge, thickening to the left of the metre stick, contains some clasts and at the near left of the figure a cluster of clasts is conspicuous. The dipping beds within the gravels are demarcated by the stone lines, with the stones dipping consistently within the beds.

Because these bedforms are also widespread throughout the channel floors in this area it is reasonable to conclude that channels and the intervening residuals supporting these bedforms were submerged simultaneously. Where such bedforms are absent on the channel floors, washing out may have occurred during waning flows, and/or mantling by postglacial sediment may have concealed them. In the first case, the channel floor

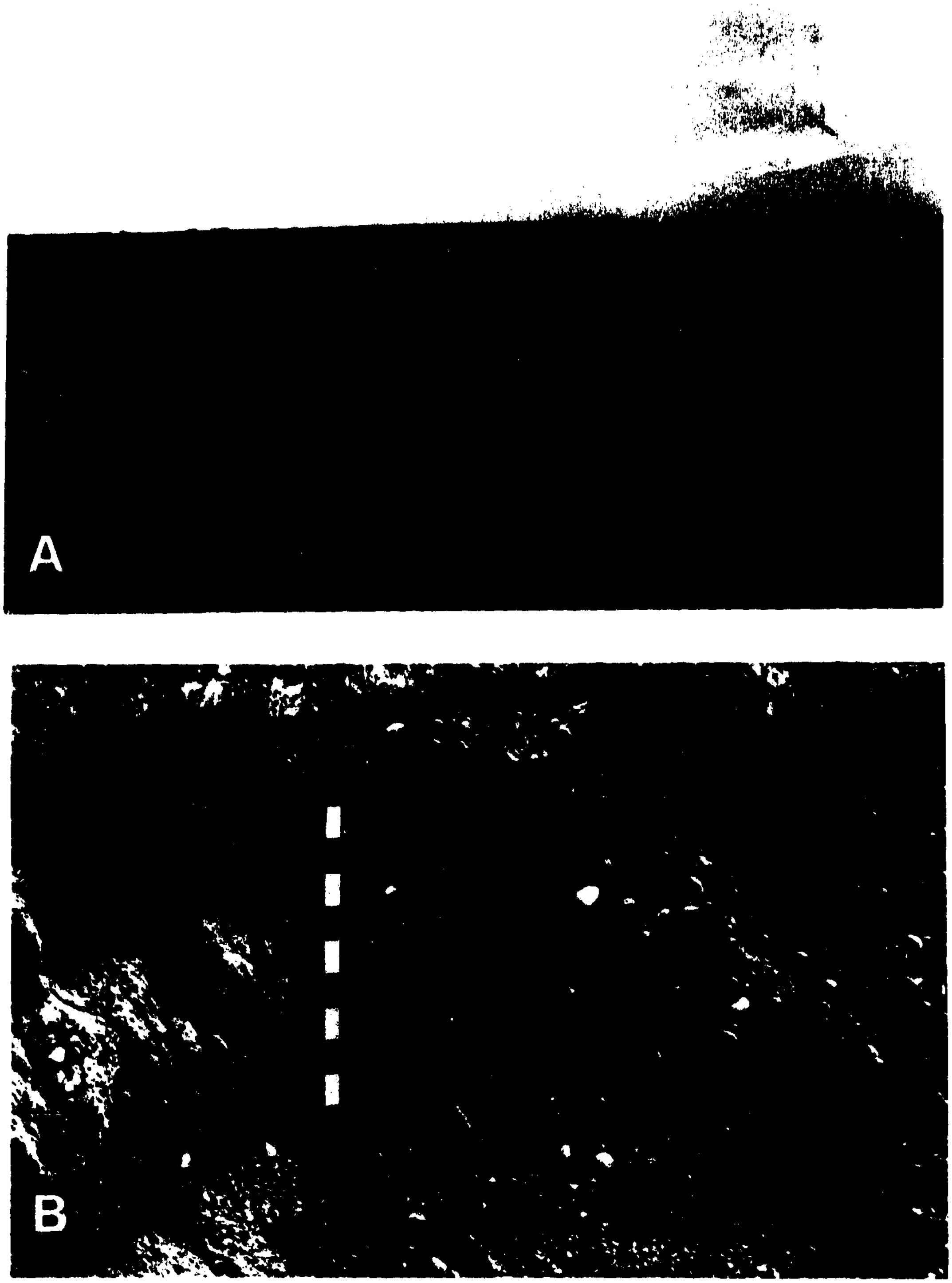


Figure 6-11: A - Long, arcuate ridges west of Hamilton Lake. Note how long grasses accentuate the troughs (looking southwest). B - Steeply dipping clasts associated with the dip of the bedform. Aeolian sediment has filled in the trough (metre stick for scale).

would become mantled with an even cover of clasts, originally found in the bedforms. This may be the case since one major, flat, channel floor displays an even cover of cobbles (this channel is closer to the diversion than sites of Figures 6-11A and B).

Interpretation

The ripples seen in Figure 6-11A are depositional bedforms that cover higher ground between adjacent channel bottoms. These bedforms are arcuate and their amplitude is muted by infilling of the troughs with aeolian sediment. Clasts found suspended in the aeolian sediment are suspected to be a product of frost heave. In the isolated case where there is a cluster of clasts suspended, a possible explanation may be the infilling of animal burrows.

OCCURRENCES OF TILL

SITE # 6

Geomorphic Setting

Till is only present in the western part of the scabland at elevations greater than the 800 m (2625 ft.) contour. Site # 6 is located in a roadcut that is transverse to the long axis of a streamlined residual (Appendix 1). Isolated occurrences of till typically form residual crests and are usually spatially limited. In many localities, till is present as streamlined caps on top of residuals that are otherwise composed of bedrock. Though there are some occurrences of glaciofluvial deposits above till deposits, till is usually found as local high points in the landscape.

Site Description

Exposed till is relatively fine grained, with limited amounts of large clasts. These fine grained tills commonly contain significant amounts of sand and may contain some local sandstone clasts. Sand in till is commonly observed as isolated clods, giving the till a mottled appearance, as the lighter colored sand contrasts with the darker matrix. Tills frequently display features that indicate deformation has occurred in the material, though till occurrences have been noted that do not have such evidence. Two till exposures that do not display deformation features are located on the southeast end of residuals. Till that has been deformed is characterized by long, attenuated sand stringers and enclosed sand balls. Figure 6-12A illustrates the deformation that has occurred within one till exposure. The lighter colored sand is observed to be attenuated throughout the section and one large body of sand is seen to abruptly curve upwards (left of the metre stick). Figure 6-12B shows attenuated sand stringers that are truncated nearly at right angles by light and dark colored bands. The cross-cutting sand body is wide at the base and narrows toward the top, where it pinches out. The sparse preservation of till in the scabland attests to the pervasive glaciofluvial erosion that occurred after the till was deposited.

Interpretation

The fact that deformation of till is not present in all exposures, even at similar elevations, indicates that deformation was localized. Attenuation of sand bodies indicates the differential movement of deformable material, with the sand bodies being stretched as finer material moved around them. Truncation of sand bodies suggests that differential pressures within the till resulted in upwards pressure release, injecting portions of the till into other material. The evidence of plastic deformation, rather than faulting, indicates that water had an important role in the formation of the structures. Saturated till and high, localized, load pressures exerted by the overlying ice, were likely the cause of the deformation and injection features observed in the section.

Figure 6-12: A - Attenuated sand stringers in a dark, fine grained till matrix (metre stick for scale). B - Truncation of sand stringers be injected sand from below.

PRESENCE OF BEDROCK IN GLACIOFLUVIAL DEPOSITS

Large bedrock blocks are present in many of the glaciofluvial deposits of the scabland. These blocks are commonly larger than 2 m in diameter and may be rounded to angular. Figure 6-13A (see, also, Appendix 1) illustrates deposits in the lee of a residual crest. These blocks are found within a gravel pit located between the two contributing components of the western large-scale channel. Excavation of this pit ceased at the trees in Figure 6-13A where large angular blocks of sandstone were encountered. These sandstone blocks are thought to have undergone limited transportation prior to deposition at this site. This concentration of bedrock blocks is thought to be at the lip of a bedrock outcrop that partially provided the turbulent wake into which the cross-bedded gravel was deposited.

Large, rounded bedrock blocks have been found in other pits, such as at Site #1. Here, the large bedrock blocks are more rounded than those in Figure 6-13A and have striations superimposed on them. The striations are aligned parallel to the long axis, in the case of the boulder in the foreground, whereas the other boulder has two well developed surfaces that display different striation alignment. These bedrock boulders were not found *in situ* so their location within the sedimentary sequence is uncertain.

Large boulders of bedrock are found in sediments that are located within close proximity of the margin between the two bedrock formations in the scabland (Figure 1-4). The presence of bedrock boulders in deposits to the east has been noted. However, these clasts are significantly smaller than the large bedrock blocks found along the formation contact. The unconsolidated sandstone of the Horseshoe Canyon Formation would not be resistant to vigorous flow conditions, capable of transporting such large clasts, without being rapidly broken down. The presence of clasts in fluvial deposits that

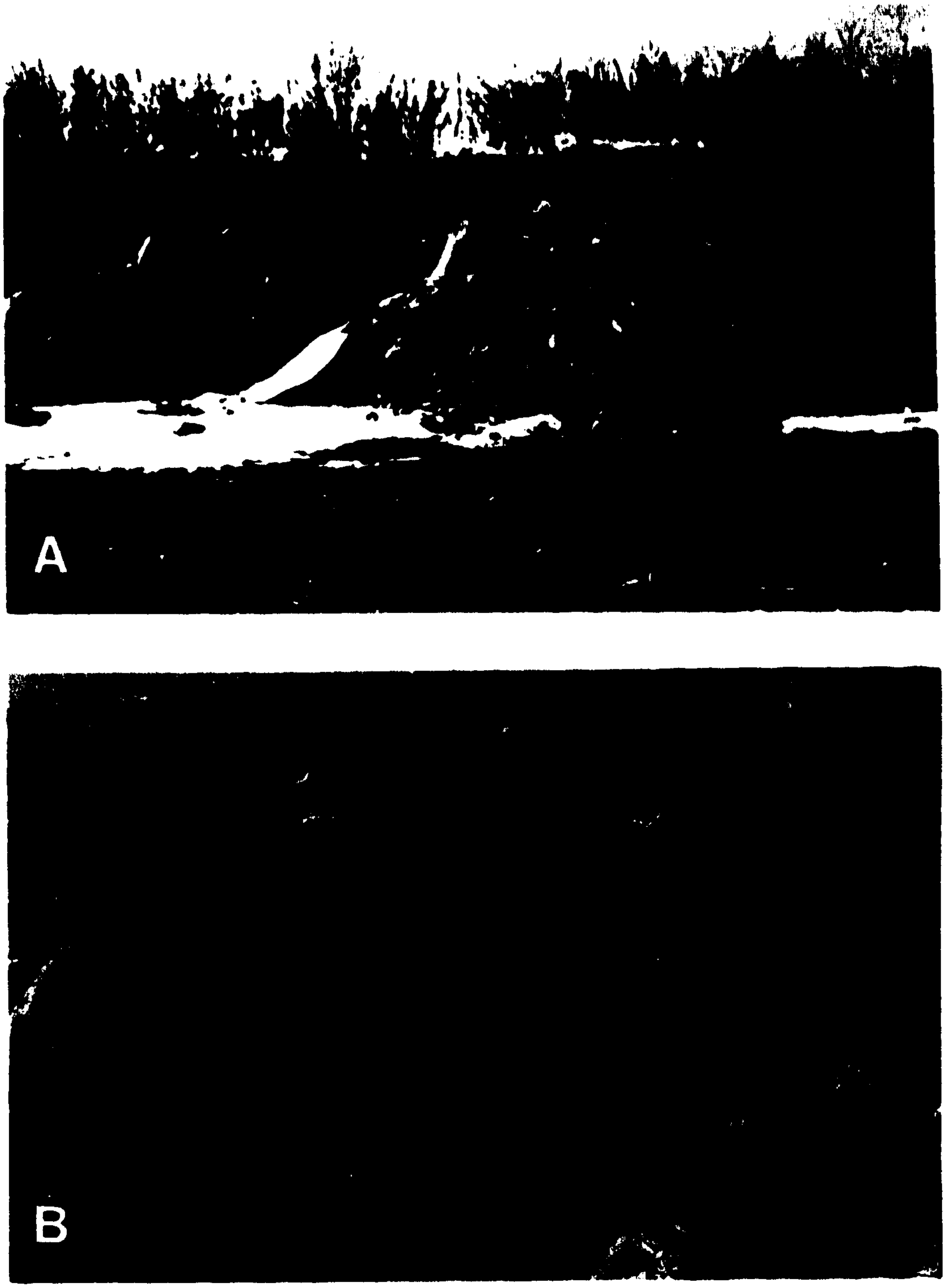


Figure 6-13: A - Large bedrock blocks excavated from pit located in the lee of a large residual. Note the angularity of the blocks. B - Striated, local bedrock boulders found at Site # 1. The boulder in the background has two sets of striations at different angles (metre stick for scale).

have, initially been glacially transported, suggests clasts underwent limited, subsequent, glaciofluvial transport. The large blocks of sandstone in Figure 6-13A indicate transport distances were inadequate to significantly round the clasts and obliterate striations before they were glaciofluvially deposited.

CONTEMPORANEOUS GLACIOTECTONISM

SITE # 7

Geomorphic Setting

This site is located in the upper reaches of the western large-scale channel, characterized by well defined dendritic channels (Appendix 1). These channels form the transition between the broad scoured zone, with isolated channels, and the broadly scoured large-scale channel. Individual channels display deposits of large boulders along the channel margins, as well as in the thalweg of the channel. Site # 7 is located along the southern margin of one small channel, slightly higher than the main channel floor. A small streamlined form, located along this southern margin, contains a excavation that is oriented transverse to the long axis of the residual and to the channel within which it is situated.

Site Description

At this site, a combination of bedrock blocks, and a heterogeneous gravel component, overlie a streamlined erosional form in bedrock (Figure 6-14). Large, local, bedrock blocks are angular and are crudely imbricated, indicating flow from the west. Interspersed with bedrock blocks are small amounts of gravel and a few, larger non-local-bedrock clasts. These gravel deposits are generally located under and/or between the local bedrock blocks and above the *in situ* bedrock. Primary bedding is apparent in the

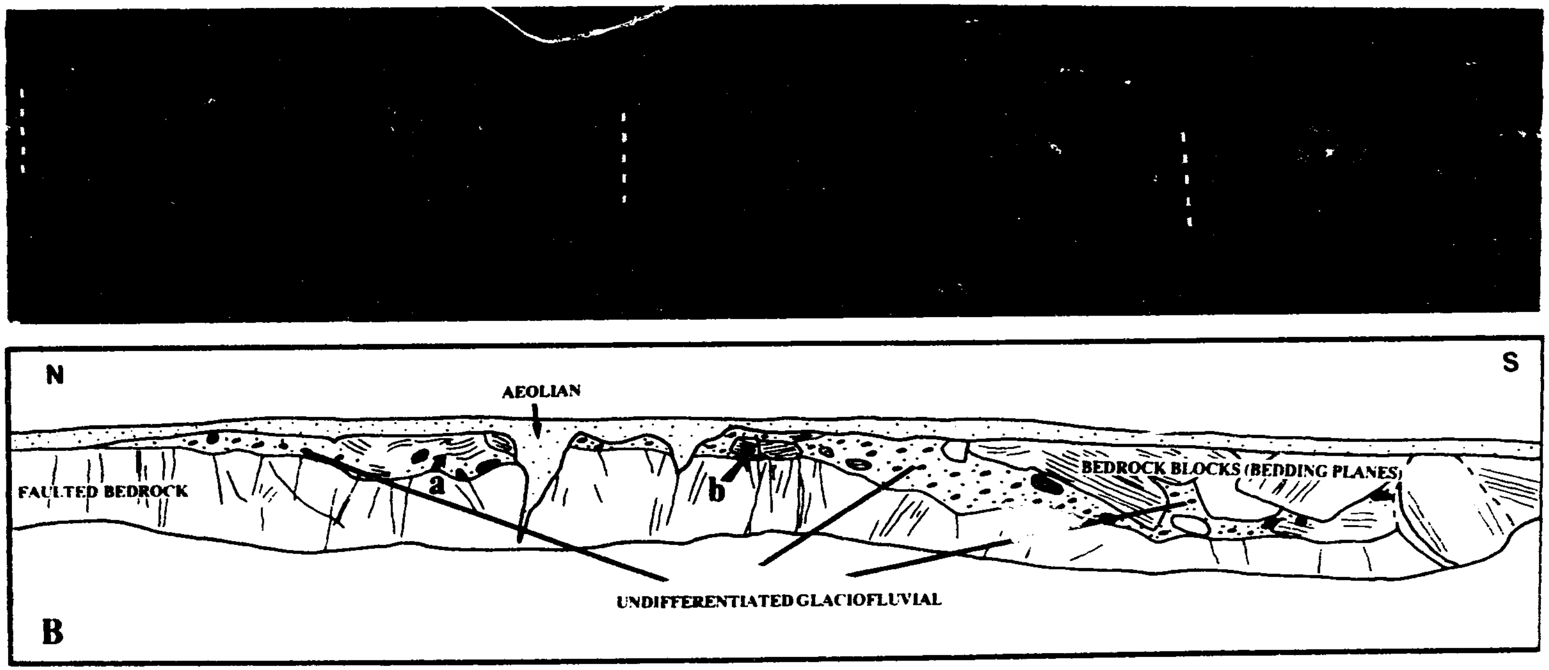


Figure 6-14: Site # 7: A small streamlined residual superimposed by imbricate local bedrock blocks and containing faults.

Note that the faults continue trough the clast at (b) and (a) is deformed around the underlying material. Metre sticks for scale.

blocks but is deformed/faulted in places. Smaller local bedrock blocks along the crest of the residual are deformed around the underlying material (Figures 6-14A and B, a). Faults have also cross-cut some clasts. One faulted clast (Figure 6-14, b) illustrates that faults (that have only small amounts of displacement) not only extend through the clast but also into the underlying bedrock, continuing to an undetermined depth.

The upper surface of the bedrock is irregular, with numerous erosional scallops appearing as concave-up boundaries (Figure 6-15A). The scallops support gravels and local bedrock blocks that appear to have been forced into the scallops. Scallops are more numerous on the southern side of the section where they are covered by the largest imbricate boulders (Figure 6-14B). The bedrock itself contains numerous faults that continue from the scalloped surface to an undetermined depth. Faults occur at different angles throughout the section. Where lower angles are found, the depth of surficial deposits is the greatest. Figures 6-14 and 6-15B show the distribution of the fault lines that penetrate the bedrock, and their associated angles.

Interpretation

The angularity of the bedrock blocks that overly the *in situ* bedrock indicates that their distance of transport was minimal. Imbrication of these blocks, and the presence of further-travelled rounded gravels, indicate that the deposits were rapidly deposited by water. Scalloping of the bedrock surface suggests that the initial glaciofluvial action eroded the form of the feature, and subsequently deposited the material. The scallops that are more prominent along southern portions of the section were protected by the overlying material. If the flow that deposited these clasts was unable to erode this surface, the scallops would have been preserved. The scallops, however, on the northern side were nearly obliterated.

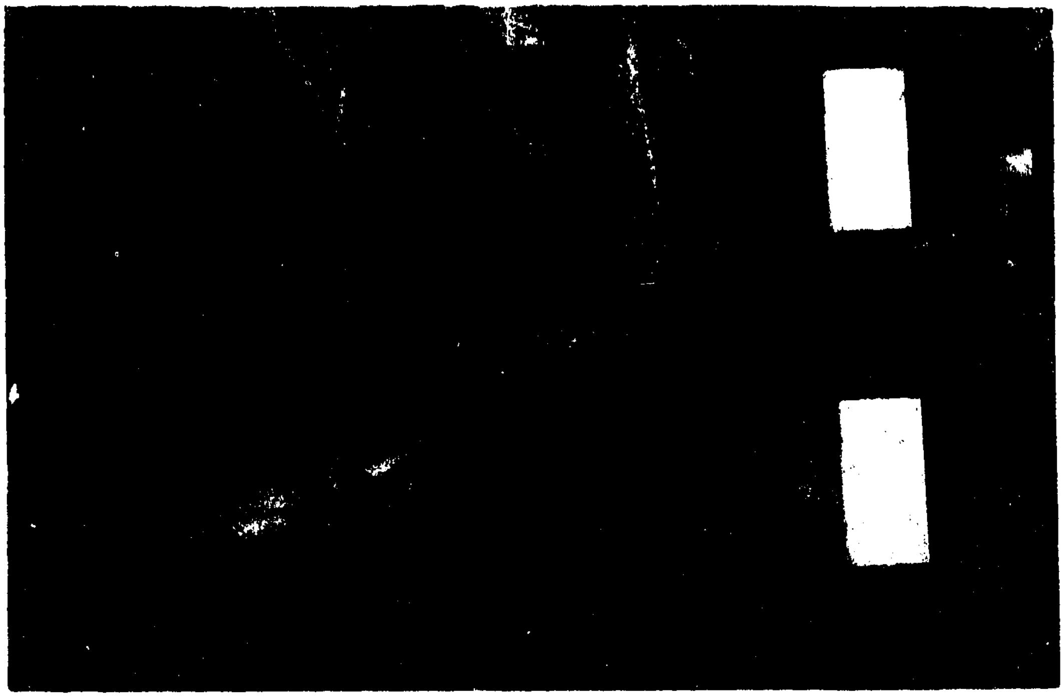


Figure 6-15: A - The contact between unconsolidated sediment and the faulted bedrock. B - Faults that converge with depth. Decimetre intervals for scale.

The faults within the bedrock and the overlying local bedrock blocks deserve note, particularly because of the relative timing of events. Clasts of bedrock are fractured by faults that continue into the underlying bedrock, suggesting that all faults occurred simultaneously. Local bedrock blocks were deposited glaciofluvially. Therefore, the depositional event must have occurred prior to the faulting. Because the fault lines extend at least to 1 m below the surface, it can be concluded that the force needed to create the faults must have been substantial.

Two possible formational environments exist for this site; subaerial or subglacial. Because the residual that contains Site # 7 lies within a channel, that forms one of the major contributaries to the western large scale channel, it can be concluded that the erosional event that formed the large channels also formed the small residual and the deposits superimposed upon it. It follows that if this primarily erosional event formed the small residual, but also deposited the sediment on top, the faults in both must have occurred after the fluvial event.

Fracturing/faulting of the bedrock may be associated with valley rebound as the overlying material is removed, however, this cannot account for the fracturing of clasts in the unconsolidated material. Another possibility is that periglacial processes formed the faults. This does not explain the deformation that is apparent in the locally derived bedrock clast at (a). Recoupling of glacier ice to its bed after the passing of a subglacial flood event provides both the necessary force to create the fracturing and deformation found in the glaciofluvial material and the genesis of the main site elements.

CHAPTER SEVEN: SUMMARY, DISCUSSION AND CONCLUSIONS

INTRODUCTION

The preceding three chapters deal with descriptions and observations of erosional and depositional features constituting an intriguing assemblage of channels and residuals in the Coronation-Spondin scabland. The current chapter argues in favour of a subglacial glaciofluvial origin for these landforms by critically evaluating traditional theories within the context of the observations that have been presented. Two primary themes in this discussion are the integration of the channel systems and the submersion of residuals in the formative flow.

SUMMARY

Channel Integration

It has been suggested that the Coronation-Spondin scabland was formed either ice marginally or proglacially. Gravenor (1956) stated that not all "spillway" channels were utilized simultaneously, thus suggesting a piecemeal formation of the channels. One of the primary arguments against an incremental formation of the scabland lies with the integrated nature of the channels.

Relief within the channels at contributary and distributary junctions indicates that differential scour occurred at these locations. More deeply scoured areas are commonly found at channel confluences, whereas high points in the channels are associated with distributary junctions. Most pertinent scour zones, that indicate an integrated system, occur at the confluences between intermediate and large-scale channels. At this type of confluence, intermediate-scale channels enter the large-scale channels at the same elevation, forming a long furrow that demarcates the margin of the large-scale channel. Furrows associated with such confluences are shallow and are observed to divert around large depositional zones, located along the western margin of the eastern large-scale channel. This diversion occurs where convergent channels, from the diversion of the western channel, have delivered large amounts of sediment into the eastern large-scale channel. Figure 6-9 illustrates the type of sediment found in this deposit, where paleoflow evidence indicates interference between the two converging flows. The lateral furrow diverts to the east at this sediment influx, joining with the lesser developed eastern lateral furrow. Distributary channel junctions give rise to smaller channels that are observed to have convex-up to undulating along-channel profiles. The integration of the channel network is upheld where thalwegs of divergent channels occur at the same elevation as the divergent junction and the convergent junction, between which the channel may rise significantly.

Another aspect of the channeled scabland indicating that channels operated simultaneously, is the absence of backflooded sediments. Sediment deposited by upvalley surges of water from deep, proglacial, flood water has been used by numerous researchers, working in the Channeled Scabland in Washington State, U.S.A., to determine multiple flooding events (see Baker and Bunker (1985) for references). Sediments that reflect backflooding are not present in the Coronation-Spondin scabland.

Submersion of Residuals

In addition to the integration of the channel network, the morphology of residuals is also important. Residuals in the scabland indicate that they were submerged in the flow, during most of the channel incision. Many residuals display superimposed forms that indicate the simultaneous existence of flow in the channels and over the residuals. Superimposed transverse ripple forms drape residuals on the top, as well as on the sides, down to the flanking channels. Ripple forms are observed to be muted and become indistinguishable at the base of the residuals. Similar transverse elements have been noted on flutings by Aylsworth and Shilts (1989), but, the mechanism proposed for their formation is different than that presented herein.

Longitudinal scours, superimposed on the residuals, also indicate submerged conditions. These scours are consistent with the orientation of scours/ridges in the large-scale channels, and represent residual crossings at the bend in the large-scale channel. Others are flanking scours that cut the residuals at low angles, creating erosional benches along the sides. These erosional benches may have slopes opposite to the slope of the larger residual upon which they are superimposed. The merging of benches from opposite sides produces a residual hierarchy.

Depositional forms also indicate submersion of residuals in the scabland. Pendant bar deposits, and deposits found high above channel bottoms, indicate that, at least during most of the scabland development, flow covered residuals at various depths. The paleoflow directions at Sites # 1 and # 2 are consistent with flow directions within the channels. Thus, the same flooding event that incised the channels deposited the cross-bedded sands and gravels with interspersed boulders. The size of the few deposits located on top and in the lee of large residuals, suggests that the formative flow was heavily laden with sediment, but sufficiently powerful as to flush most of that sediment through the channel network. Thus, only those locations that provided protection from the highly erosive flow were capable of preserving large gravel deposits.

Residuals in the scabland are generally well-rounded in profile and show 3-D streamlining, by a flow that submerged them. The smooth margins of the residuals lead to the conclusion that flow associated with channel formation was also eroding the residuals while they were submerged. This conclusion is supported by the fact that small superimposed "knobs" were found to be rounded on the top of some residuals, in conjunction with shallow depressions (filled with boulders) which appeared to be eroded into bedrock. These shallow depressions are interpreted to be waning flow scours, similar to waning flow scours associated with incision in braided river systems (Ashmore 1979).

Character of the Flooding Event

The flooding event that created the Coronation-Spondin scabland was highly erosive and turbulent. Important lines of evidence that support this conclusion include: the relative paucity of deposits; long longitudinal grooves found on the floors of the channels; streamlined residuals; and the size of clasts moved by the flow. Deposits in the scabland are composed of a wide range of particle sizes that commonly display evidence of rapid deposition from a highly turbulent flow. These types of deposits have been described for different sedimentary environments and have been generally attributed to deposition from hyperconcentrated flows (Lord and Kehew 1987). The infrequent occurrence of deposits in the scabland reflects a predominantly erosional event where deposition occurred only in the lee of major obstructions, or in locations of significant flow expansion.

Longitudinal grooves have been linked with the evolution of proglacial spillways on the prairies (Kehew and Lord 1986) and to the catastrophic drainage of Glacial Lake Missoula on the Columbia Plateau, U.S.A. (Baker 1978b). Longitudinal grooves have been shown, experimentally, to coalesce and form a single inner channel (Shepherd and Schumm 1974). This coalescence of longitudinal grooves has thus been linked to the transition from channel forms with anastomosing patterns to deeply incised inner channels (Kehew and Lord 1986). Streamlining of residuals in subaerial flooding events has also been noted by Kehew and Lord (1986) who speculated that prolonged flow in anastomosing patterns results in streamlining of the residuals that approach the lemniscate form. Streamlining of residuals also involves a tapering of the height of a residual in a downflow direction, if the residual has been submerged. Komar (1983) determined that the "best" streamlining occurs when water is just sufficient to "top" the residual, producing supercritical flow. Baker (1978b) categorized residuals that had been submerged, and thus formed subfluvially, from those that had been only partially submerged or remained above the high water surface. Tapering tails and crestlines (decreasing vertically downflow) of residuals in the Coronation-Spondin scabland imply that all residuals were submerged, though the undulatory tops of some residuals imply only shallow submersion. It is unlikely that supercritical flow could occur in a subglacial environment, however, flow constriction over the residual by an irregular ice roof could enhance erosion forming a similar streamlined shape.

Boulder lags located on channel floors reflect powerful flows capable of moving extremely large clasts (Figure 4-5). The clustering of these boulders, and their location in the middle of channels, suggest that they were moved as bedload. As the flow waned, the largest clasts ceased movement first, with the smaller clasts collecting around such stabilized nuclei. Sudden flow cessation associated with the falling limb of a flood hydrograph, in addition to the possibility of individual channels being abruptly cut off from flow, could have formed such deposits.

Glaciotectonic Activity

The Coronation-Spondin scabland contains evidence of two glaciotectonic episodes. The first occurred before channelization of the scabland because the folded strata are found to compose part of channel floors (found along the western limit of the scabland) as well as adjacent residuals. This folding has a northwest-southeast orientation, similar to the Neutral Hills, located northeast of the scabland (see Figure 1-2). The second episode of glaciotectonic activity is illustrated by the features at Site # 7 where fracturing of bedrock composing the residual and of superimposed locally derived bedrock clasts has occurred.

Two separate episodes of glaciotectonism occurring in the scabland require explanation. It is possible that the two tectonic episodes represent two separate glacial advances (or glaciations), with the scabland-forming event occurring in the interim by subaerial flooding. Alternatively, the first episode of glaciotectonic activity may have occurred during glacial advance and the second as glacier ice recoupled to its bed after the hypothesized subglacial flooding event.

DISCUSSION

Catastrophic subglacial sheetfloods, originally proposed by Shaw (1983), have been recently associated with the formation of a wide range of landforms traditionally attributed to direct ice contact. This theory of sheetfloods originally stemmed from the striking similarity of some drumlins and erosion marks made by separated, turbulent, fluid flows. The idea that turbulent flows in subglacial sheetfloods carved up into the ice, as well down into sediment and bedrock, was followed up in subsequent papers (Shaw and Kvill 1984, Shaw and Sharpe 1987, Shaw *et al.* 1989). Some of the forms that resulted from these sheetfloods include spindle, parabolic and transverse asymmetrical drumlins. These are strikingly similar in shape to the inverse of erosion marks. In addition to these large, inverted versions of erosion marks produced by separated flows, smaller "s-forms" (formerly known as "p-forms") have also been attributed to large subglacial floods (Shaw and Gilbert 1990). This theory makes possible the explanation of many glacigenic landforms using variations in flow characteristics of single catastrophic events.

Catastrophic floods have also been linked to the formation of tunnel valleys (Wright, 1973, Boyd *et al.* 1988). Loncarevic *et al.* (1992) suggested catastrophic subglacial formation of tunnel valleys on the Scotian Shelf, on the basis of overspill channels on the Laurentian Fan. These resemble spillway channels found on the Canadian prairies (Kehew and Lord 1986), and are found to contain sand interbedded with large turbidite beds. It has been suggested that a transition from sheetflow to channel flow occurs (Shaw and Kvill 1984). Sheetflows are unstable, and locally high and low pressures tend to concentrate erosion, resulting in channelization (Drewry 1986). The local pressure gradients expected in a nonuniform bed would discount the presence of a thin Weertman film (Nye 1976). Shaw and Gorrell (1991) suggested that the association of tunnel channels and eskers indicates channeling of a waning flood. Catastrophic, subglacial outbursts have also been suggested as an alternative hypothesis for the formation of Rögen moraine (Fisher and Shaw 1992) and hummocky moraine (Shaw 1988a). Recently, subglacial sheetflooding events have been related to formation of large-scale landform associations in central and southern Alberta (Rains *et al.* in press).

There is a broad zone, east of the Buffalo Lake Moraine and west of the Viking Moraine, where bedrock is at or near the surface. Possible reasons for the paucity of glacigenic deposits in the area, called the Torlea Flats, were earlier addressed by Gravenor and Bayrock (1955) and Gravenor (1956). They noted evidence for one glaciation in the area, but, since there is evidence for multiple glaciations elsewhere in the province, they reasoned that the last glaciation removed the previously deposited material (Gravenor and Bayrock 1955). They also concluded that the poor preservation of glacigenic deposits was related to the nature of the bedrock in the area. Gravenor and Bayrock (1955) hypothesized that the last glacial advance removed drift of the previous glaciation, became packed with bentonitic clays, which reduced frictional resistance and, as a result, little till was deposited. Warren (1937) stated that the "Torlea Flats" were subject to erosion after till deposition, leaving a flat plain. It is this removal of material from the Torlea Flats that has been attributed to subglacial meltwater associated with the Livingstone Lake "event" (Rains *et al.* in press).

Rains *et al.* (in press) suggested that much of the hummocky terrain in central Alberta represents erosional remnants of a mega-scale, subglacial, flooding event called the Livingstone Lake "event". This subglacial flood formed the "cavity fill" drumlins around Lake Athabasca, northern Saskatchewan, and giant flutings near the town of Athabasca, Alberta. The initiation of this flood may have occurred simultaneously with discharges from Cordilleran sources, creating numerous interference zones. Interference vortices, and the anastomosing paths taken by this flood, also may have been responsible for the erosion of hummocks, including those around the Chain Lakes-Sullivan Lake area. The erosional nature of hummocks in this area is indicated by the presence of some that are composed of bedrock, where deformation structures in the bedrock do not conform to the surface forms of the hummocks.

Regional-scale features add credence to this "flood" theory in that the hummocky terrain west of Sullivan Lake appears to be defined by a large horseshoe scour (Figure 3-1) similar in shape to the Hand Hills to the southwest (Young 1991). The eastern margin of this hummocky zone, resembling one arm of a large horseshoe scour, produces a long sweeping outline west of the Coronation-Spondin scabland. A large field of giant flutings south of the scabland, mapped by Skoye (1990), appears to be truncated northward by shallow scabland channels. The flow that formed hummocky terrain north of Hanna, the giant flutings, and undulating terrain (areally consistent with solonetzic soils) occurred before formation of the scabland (Rains *et al.* in press). Thus, formation of the Coronation-Spondin scabland may have been related to either (1) a later, smaller, discrete, flow event caused by drainage of small, subglacial bodies of water, or (2) the waning flow of the Livingstone Lake "event".

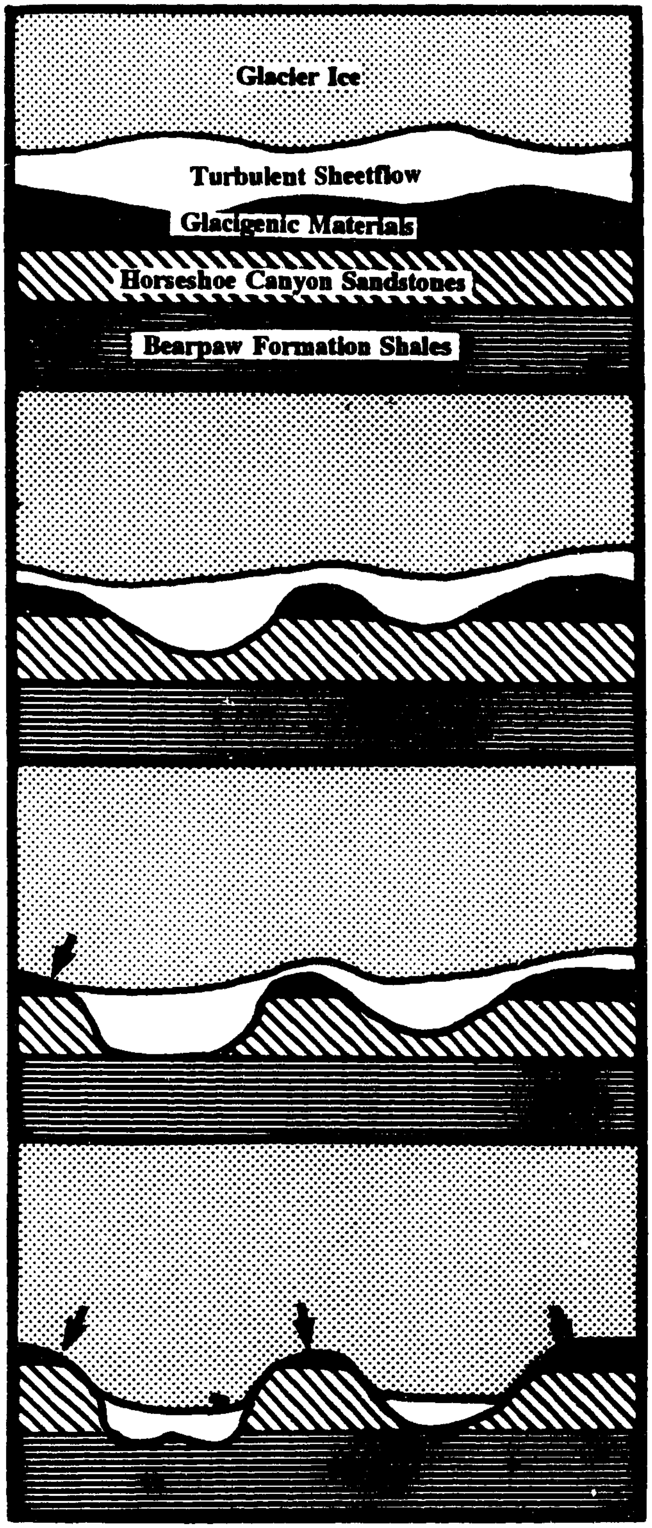
The orientation of the channels and residuals, plus the broad s red zone located upflow of the channels, suggest that the source of the formative water flow was the Sullivan Lake basin. However, the size of the Sullivan Lake depression does not appear sufficient to supply such a large amount of proglacial water. Shoemaker (1992a) suggested that the dynamics of the Laurentide ice sheet were dominated by surges that episodically changed the ice profiles. Surging resulted in widespread crevassing that enabled water to penetrate from possible supraglacial sources (Shoemaker 1992a). In addition to hypothesizing possible supraglacial water sources, Shoemaker (1992b) suggested that reversed drainage could have contributed to the ponding of some subglacial water. He also speculated that the cascading effect of multiple, small, subglacial lakes draining into others, set off a domino effect similar to that envisaged for some proglacial lakes (Kehew 1982). Channel systems, similar in size to the Coronation-Spondin scabland, in other parts of Alberta (Shetsen 1987, 1990), probably represent multiple, subglacial, cavity drainage events.

During the waning stages of the Livingstone Lake "event", it is likely that ice recoupled first to high points of the bed (such as the hummocky terrain south of Sullivan Lake) and, with the decreased amount of water, this combined to produce a more easterly flow direction. Water would then have been constricted by a rapidly-subsiding ice roof, concentrating meltwater flow along discrete paths. Irregularities in the bed, and in the roof of the ice, contributed to the concentration of flow into a relatively narrow zone east of Sullivan Lake. The latest stages of this flood were characterized by increased channelization as the discharge dropped. Such a sequence of events has been suggested for other areas where sheetfloods, forming drumlins, evolved into large-scale, anastomosing, tunnel channels (Brennand and Shaw in prep).

The upflow limits of the Coronation-Spondin scabland were characterized by a broad sheet flow (Figure 4-1) which became largely channelized as the bedrock contact between the Horseshoe Canyon and Bearpaw Formations was encountered (Figure 1-4). Channel incision near this bedrock contact, and the upflow extension of channel segments, resulted in contricted sheetflow over some residuals, that formed subtly-expressed margins of these residuals. In the central residual zone, flow depths were minimal over much of the area, except were broad breaches in the zone carried flow eastward to join with the eastern large-scale channel. Figure 7-1 illustrates the probable, generalized sequence of events that formed the Coronation-Spondin scabland.

Phase 1

During Phase 1, the formative outburst flood was followed by a decrease in



Phase 1

- Discharge of the Livingstone Lake "event" begins to wane.
- Ice roof and bed irregularities cause localized scour.

Phase 2

- Localized scours give rise to channel forms
- Rapid incision through glacigenic materials and Horseshoe Canyon Formation sandstone forms concave-up channels.
- Hydrostatic pressures force flow over the residuals forming convex-up channel thalwegs.

Phase 3

- Lateral erosion becomes important as channels encounter more resistant Bearpaw Formation shales.
- Localized contact between glacier ice and the highest residuals (arrow).

Phase 4

- Deposition of boulders occurs.
- Deformation of saturated tills and small-scale glaciotectonism occur as the ice recouples to the bed (arrows).

Figure 7-1: Development of the Coronation-Spondin scabland characterized by progressive channelization of a subglacial sheetflood.

discharge, and constriction of flow resulted in the broad scoured zone between the main scabland tract and Sullivan Lake. Downflow of this zone, flow adopted several paths that fanned out as they encountered the bedrock contact. At that time, bed irregularities and serendipity resulted in the partial channelization of the flow. Localized occurrences of till were preserved on high residuals. The partial breakdown of the primary, formative, sheetflow into channelized flow thus began.

Phase 2

During Phase 2, rapid incision occurred through the Horseshoe Canyon Formation, creating predominantly concave-up channels. Hydrostatic pressure of water flowing over the residuals temporarily kept ice from recoupling with the tops of most residuals. Flow over the residuals formed large expanses of erosional ripple forms, and subtle channel forms. Sediment transport over the top of these residuals supplied the growing pendant bars with sediment. Small-scale channels, that captured a significant amount of water from the intermediate-scale channels, developed convex-up along channel profiles. Further dissection of residuals was arrested prematurely in places as the water sources locally shut off. Termination of flow within residual-dissecting channels resulted from flow capture by the larger channels. Larger channels are dominant over smaller ones because large discharges are associated with small hydraulic gradients (Röthisberger and Lang 1987). Thus, a pressure gradient was set up between channels such that flow was diverted from smaller to larger channels. In addition, hydrostatically-driven water formed scours that flank the residuals at low angles. High pressures forced water, that formed these scours, along the margin of the residuals.

Phase 3

This phase was characterized by broadening of the major channels as they were eroded to or below the contact of the two regional bedrock types. Because the Horseshoe Canyon Formation sandstones were more easily eroded than the underlying Bearpaw Formation shales, lateral erosion of channels dominated over vertical incision until the Bearpaw Formation shales were reached. As discharge waned, and flow was increasingly carried in the channels, less water was contributed to flow over the residuals. The glacier ice then regained partial contact with some of the residuals. During this recoupling of the ice and bed, the partially channelized flow over the residuals also formed progressively shallower sheetflows that created the undulating terrain found on the surface of some residuals.

Phase 4

During Phase 4, the final episode in formation of the Coronation-Spondin scabland, discharge through most of the channels had ceased and recoupling of the ice to many channel bottoms was occurring. Boulder deposits accumulated from the rapidly declining flow. When the flow shut off completely, recoupling of the glacier sole to the saturated bed produced some plastically-deformed injection features (Figure 6-12). Also, glaciotectonic fracturing occurred in local bedrock slabs that had been glaciofluvially perched on top of at least one residual (Figures 6-14 and 6-15). Recoupling of the ice and bed then first concentrated stress on tops of the residuals. Where channels had markedly oversteepened the residual margins, slumping has occurred (Figure 5-7). Slope failures would have been likely to occur when the substrate was saturated, thus decreasing internal strength of the materials.

CONCLUSIONS

Landform assemblages in central Alberta attest to erosion by catastrophic subglacial floods. Scoured bedrock, giant flutings, and large erosion marks illustrate the importance of secondary flows within the turbulent flood(s) which moulded the landscape. The unconsolidated Late Cretaceous bedrock, found in central Alberta, was easily eroded by turbulent sheetflows, resulting in low-relief landforms. Only subtle expression of some landform-suites is apparent in the field, but recent technological advances have enabled detection.

The concept of subglacial flooding has made it possible to link different types of glacial landforms in central Alberta to a single process. Further research in the region must investigate associated landforms within the context of the Livingstone Lake "event" in order to verify or modify this theory. Hummocky terrain in central Alberta may be, in part, a result of differential erosion but this concept needs sedimentological verification. Ripple-like forms, located along the margin of the proposed flood path (northeast corner of Figure 3-1), may also be erosional, although their association with this flooding event is, as yet, unclear. The genesis of these landforms, along margins of this hypothetical flood, is crucial in the development of a cohesive interpretation of glacial landforms in Alberta.

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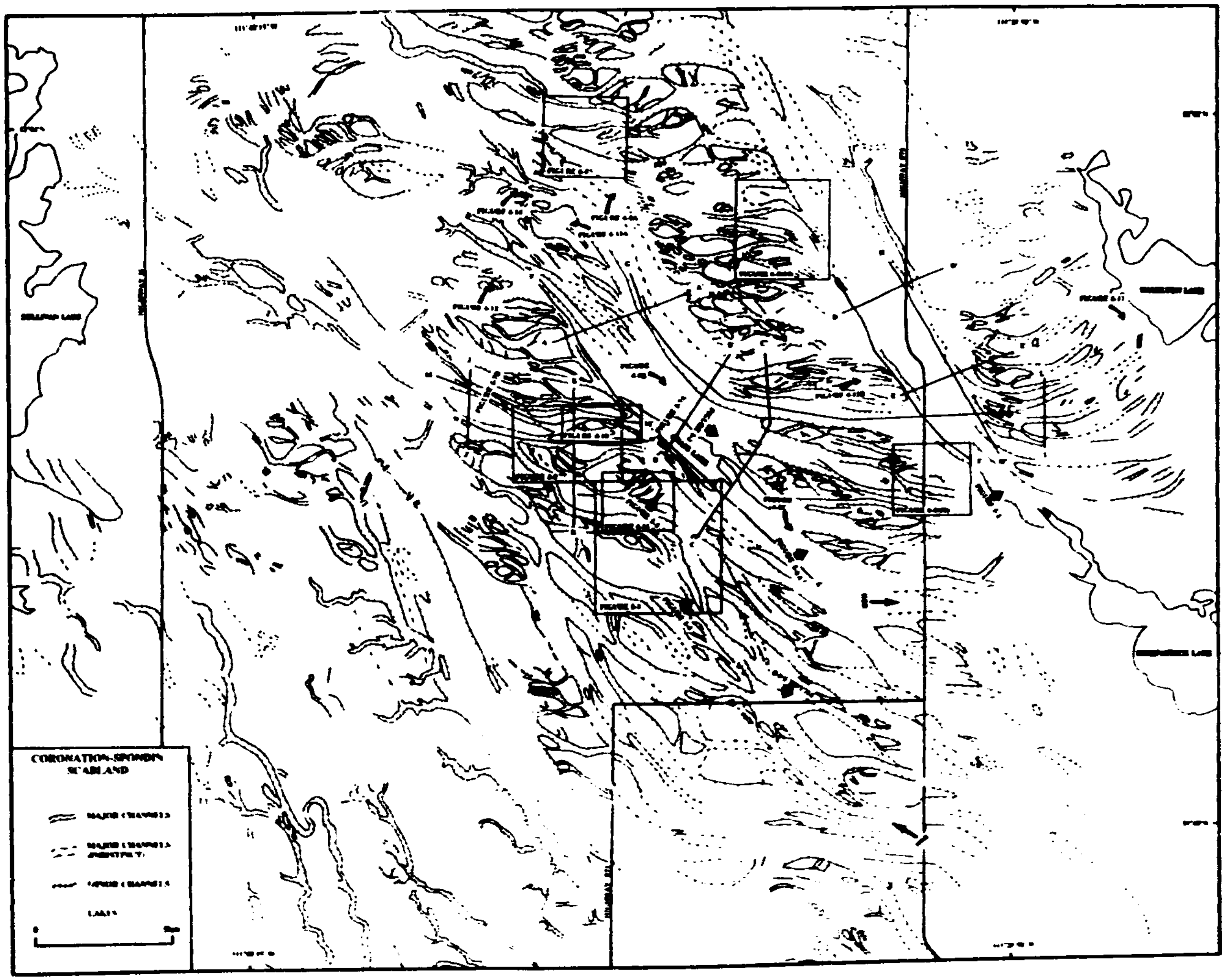

Appendix 1: Locations of Figures referred to in Chapters 4, 5 and 6. Compiled from aerial photographs (see Appendix 2).

APPENDIX 2: COMPILATION INFORMATION

SATELLITE IMAGERY: Figures 3-1 and 4-1

Data Type: LANDSAT 4 MSS, Band 3
Acquired: January 4, 1984, at 9:51a.m.
Location: Path 41/Row 24
Enhancement used: Linear Contrast Stretch

AERIAL PHOTOGRAPHS: Figures 4-2, 5-1 and Appendix 1

Compilation involved detailed morphologic mapping from aerial photographs.

(1) AS 1336 photo #s: 65-75, 117-129, 170-184, 223-242, and 277-290.
Maps Alberta, Department of Environmental Protection

(2) CR 462 - 5200 photo #s: 4-18 and CR 466 - 5201 photo #s: 5-20.
National Airphoto Library

DIGITAL ELEVATION MODELS (DEMs)

Data Source:
Alberta Forestry, Lands & Wildlife Land Information Services Division
50th Street Atria, 4949-94B Avenue
Edmonton, Alberta, Canada T6B 2T9

Data Scale: 1:20000 DEMs with 25m X 25m grid cells

Method of Capture: Photogrammetry

Processing:

The DEMs were prepared for processing using software developed in the Department of Geography, University of Alberta, Edmonton, Alberta.

Processing was accomplished using an unpublished display and analysis package called Terra Firma. This package was developed by:

J. Ronald Eyton
Department of Geography
University of Alberta
Edmonton, Alberta
T6G 2H4

Figures 4-3, 4-4, 4-7, 4-9, 4-12

Were compiled by creating computer generated contours from the DEMs from [illegible] the profiles could be obtained, manually. The raw grid data was [illegible]thed and augmented, using modules from Terra Firma, to produce usable [illegible]tour maps.

Figures 4-8, 4-10, 4-11, 5-2, 5-3, 5-4, 5-5, 5-6

Are 3-D perspective views, created from the DEMs using software developed in the Department of Geography.

Figure 4-6

Was obtained directly from the raw DEM information using a perspective 3-D mesh as above, but, only one column of data was used and the look angle was set to 0°.