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D.S. Lemmen, R.E. Vance, I.A. Campbell, P.P. David, D.J. Pennock,
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Cover illustration

Active, compound parabolic sand dune about 18 km south of the town of Sceptre, in the Great Sand Hills of southwestern Saskatchewan. The slipface of the dune has been monitored by P.P. David since 1966, and is migrating eastward at an average rate of 2.1 $m \cdot a^{-1}$. The uppermost branches of a dead poplar tree, which the dune has advanced around, are visible in the central part of the photo. Sand dunes are a dramatic example of locally dynamic geomorphic environments in the southern Canadian prairies that are highly sensitive to climate variability and change. Photo by S.A. Wolfe. GSC 1997-86

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GEOMORPHIC SYSTEMS OF THE PALLISER TRIANGLE, SOUTHERN CANADIAN PRAIRIES: DESCRIPTION AND RESPONSE TO CHANGING CLIMATE

Abstract

The Palliser Triangle of southeastern Alberta and southwestern Saskatchewan is characterized by a variable climate, strong annual moisture deficit, and recurrent drought. Geomorphic systems in such environments are often sensitive to even minor changes in climate. Since climate changes in the twenty-first century are expected to include more frequent drought, geomorphic systems are likely to be affected in ways that threaten sustainable activities in some areas.

This review considers four geomorphic systems: eolian, fluvial, mass wasting, and soil redistribution. Soil redistribution integrates a number of lower-level systems, and is of greatest importance with respect to sustainable land management. A qualitative assessment of the potential impacts of four climate change scenarios on each of these geomorphic systems indicates the following:

1. *Eolian landscapes are the most sensitive to climatic variability, with the region lying near the threshold of extensive eolian activity.*
2. *Fluvial systems are the least predictable in terms of response to climate change.*
3. *Climate influences the frequency of mass wasting processes by modifying the regional groundwater table and determining antecedent moisture conditions.*
4. *The principal agents of soil redistribution are wind, water, and tillage. Both wind and water erosion are closely related to extreme climatic events. Human activities remain the most critical factors influencing agricultural soils.*

Identification of possible responses to climate change sets the stage for proactive land management: facilitating rapid adaptation or implementation of mitigation procedures when reliable, long-term regional climatic projections are available, or when trends can be clearly defined through monitoring.

Résumé

Le triangle de Palliser, qui se situe dans le sud-est de l'Alberta et le sud-ouest de la Saskatchewan, se caractérise par un climat variable, un déficit hydrique annuel élevé et une sécheresse récurrente. Les systèmes géomorphologiques de tels milieux sont souvent sensibles au moindre changement climatique. Puisque les changements climatiques du XXI^e siècle devraient augmenter la fréquence des sécheresses, les systèmes géomorphologiques seront vraisemblablement modifiés et menaceront les activités de développement durable dans certaines régions.

Dans la présente étude sont abordés quatre systèmes géomorphologiques : les processus éoliens et fluviatiles, les mouvements de masse et la redistribution des sols. La redistribution des sols intègre un nombre de systèmes de niveau inférieur et est de la plus haute importance pour la gestion durable des terres. Une évaluation qualitative des répercussions potentielles de quatre scénarios de changement climatique dans chacun des systèmes géomorphologiques met en lumière les points suivants :

1. *Les paysages façonnés par le vent sont les plus sensibles à la variabilité climatique, étant situés dans une zone proche du seuil des activités éoliennes intenses.*
2. *Les systèmes fluviatiles sont les moins prévisibles sur le plan de la réaction au changement climatique.*

3. *Le climat influe sur la fréquence des mouvements de masse en modifiant le niveau de la nappe phréatique régionale et en déterminant les conditions d'humidité préalables.*
4. *Les principaux agents de la redistribution des sols sont le vent, l'eau et le labourage. L'érosion tant par le vent que par l'eau est étroitement liée à des événements climatiques extrêmes. Les activités humaines demeurent le facteur le plus critique de la modification des sols agricoles.*

L'identification des réponses possibles au changement climatique marque la première étape d'une gestion proactive des terres : faciliter l'adaptation rapide ou l'application de méthodes d'atténuation lorsqu'on a accès à des prévisions climatiques à long terme fiables à l'échelle régionale ou lorsqu'on peut définir avec clarté les tendances grâce à un suivi.

SUMMARY

Climate is a critical, extrinsic, independent variable in most geomorphic systems. Subhumid to semiarid regions like the Palliser Triangle, containing landscapes close to threshold conditions, are particularly vulnerable to climate change. To prepare for the possible consequences of future climate change, this report presents a regional-scale examination of four key geomorphic systems: eolian, fluvial, mass wasting, and soil redistribution. By outlining the sensitivity of each to climate change, it is possible to elucidate potential impacts on the landscape, as well as on human activities. All of these systems exhibit sensitivity to recent climatic variability, with soil erosion being of greatest importance with respect to sustainable land management. Given that significant uncertainties remain concerning the characteristics of future climate, the concluding discussion of this report considers the potential impacts that four simple climate change scenarios would produce in each of these systems.

Despite a subhumid climate characterized by long- and short-term variability, a strong moisture deficit, and recurrent drought, the Palliser Triangle is one of Canada's, and the world's, most important agricultural regions. However, General Circulation Model (GCM) simulations of climate under enhanced concentrations of atmospheric greenhouse gases (carbon dioxide, methane and nitrous oxide, among others) suggest that increased temperature and decreased growing-season precipitation will produce more frequent droughts across much of the northern Great Plains. Concerns over how such changes will affect the region's critical land and water resources led to the establishment of the Palliser Triangle as one of the Geological Survey of Canada's Integrated Research and Monitoring Areas (IRMA). The information in this report provides a background for geomorphic field studies and landscape-sensitivity mapping that is being conducted as part of Palliser Triangle IRMA.

SOMMAIRE

Dans la plupart des systèmes géomorphologiques, le climat est une variable indépendante extrinsèque critique. Les régions subhumides à semi-arides, comme le triangle de Palliser, où les paysages se trouvent dans des conditions proches des valeurs seuil, sont particulièrement vulnérables au changement climatique. Pour se préparer aux conséquences possibles du changement climatique futur, nous examinerons quatre systèmes géomorphologiques clés à une échelle régionale : les processus éoliens et fluviatiles, les mouvements de masse et la redistribution des sols. En mettant en évidence la sensibilité de chaque système au changement climatique, il est possible d'élucider les modifications que pourraient subir les paysages ainsi que les activités humaines. Ces systèmes ont tous réagi aux variations climatiques récentes, l'érosion du sol étant d'une importance cruciale pour le gestion durable des terres. Étant donné qu'il reste des incertitudes significatives concernant les caractéristiques futures du climat, la dernière partie de la discussion porte sur les effets prévus selon quatre scénarios climatiques simples dans chacun de ces systèmes.

Malgré un climat subhumide caractérisé par une variabilité à long et à court termes, un déficit hydrique élevé et une sécheresse récurrente, le triangle de Palliser est l'une des régions agricoles les plus importantes au Canada et dans le monde. Cependant, les simulations par le modèle de circulation générale du climat caractérisé par des concentrations accrues de gaz à effet de serre (dioxyde de carbone, méthane, oxyde d'azote, etc.) indiquent qu'une hausse de la température et une baisse des précipitations durant la saison de croissance augmenteront la fréquence des sécheresses dans la grande partie du nord des grandes plaines. Les préoccupations soulevées par la façon dont ces changements influeront sur les ressources vitales en terres et en eau de la région sont à l'origine de l'inclusion du triangle de Palliser dans les zones de recherche et de suivi intégrés (ZRSI) de la Commission géologique du Canada. Les informations contenues dans le présent rapport servent de base aux études géomorphologiques réalisées sur le terrain et à la cartographie de la sensibilité des paysages dans le cadre de la ZRSI du triangle de Palliser.

Eolian processes and landforms represent the most sensitive of the four geomorphic systems to climatic variability, and are likely the most predictable in their response to climate forcing. Wind erosion is widespread within the Palliser Triangle, owing to limited relief and a paucity of natural obstructions to wind flow. Windblown sediments of varying grain sizes produce characteristic landforms including sand dunes, silty to fine-grained sand sheets and loess, as well as loamy sediments forming cliff-top deposits. Eolian activity limits grazing capacities in dune regions, and has other direct impacts on human activities (e.g. dune migration across transportation corridors). However, the greatest value derived from understanding and monitoring eolian processes relates to their role as sensitive indicators of instability in larger, less responsive geomorphic systems.

Sand dunes cover more than 3400 km^2 of the Palliser Triangle. All are part of the parabolic dune assemblage; they are 'wet-sand' dunes (with moisture contents typically between 4 and 8%) and include a variety of associated features besides the basic parabola form. Most dune areas in the Palliser Triangle are stable at present, containing only a few active dunes (<0.5% by area). Aerial photographs show that although eolian activity declined from the 1940s to the 1980s, when relatively humid climatic conditions prevailed, active sand surfaces markedly expanded in some areas in rapid response to the drought years of the 1980s. The rate and style of dune stabilization depends on climatic conditions and the ability of the dune sand and underlying sediments to absorb and retain moisture.

The conditions necessary for eolian activity: sediment supply, sufficiently strong winds, and a locally sparse to absent vegetation cover, existed on a regional scale in the Palliser Triangle during Late Wisconsinan deglaciation. Sheet sand and loess began forming as soon as source deposits were exposed, while dunes formed by dry adiabatic winds emanating from the retreating Laurentide Ice Sheet would have had very different orientations than Holocene dunes. Extensive activity may have been briefly interrupted by a humid period just before 10 ka, promoting development of soil horizons on most eolian deposits. In the early Holocene, the climate became drier than at present and extensive eolian activity was reinitiated. This period of extensive eolian activity may have continued unabated until only a few thousand years ago, and was succeeded by a protracted phase of dune stabilization in the Late Holocene. The changes in extent of eolian activity caused by modern weather fluctuations, as well as changes in the past few centuries documented by historical accounts and

Les processus et les modelés éoliens représentent celui des quatres systèmes géomorphologiques le plus sensible aux variations du climat, donc le système le plus prévisible quant à sa réponse au forçage climatique. L'érosion par le vent est partout visible dans le triangle de Palliser, du fait que le terrain y est peu accidenté et que les obstacles naturels à l'écoulement du vent y sont rares. Les sédiments de granulométrie variable transportés par le vent produisent des formes caractéristiques, notamment des dunes de sable, des nappes de sable à grain silteux à fin et des loess ainsi que des sédiments loameux formant des dépôts sur le sommet de falaises. L'activité éolienne limite les capacités de pâturage dans les régions dunaires en plus d'avoir des incidences directes sur les activités anthropiques (p. ex. la migration des dunes dans les corridors de transport). Toutefois, la compréhension et le suivi des processus éoliens sont liés au rôle de ceux-ci comme indicateurs sensibles d'instabilité dans des systèmes géomorphologiques plus vastes mais moins fragiles.

Dans le triangle de Palliser, les dunes de sable couvrent plus de 3 400 km^2. Elles font toutes partie de l'assemblage de dunes paraboliques. Ce sont des dunes de «sable humide» (teneur en humidité variant habituellement entre 4 et 8 %) et elles comprennent une gamme d'éléments associés outre la forme parabolique de base. La plupart des dunes dans le triangle de Palliser sont actuellement stables, mais quelques-unes sont actives (<0,5 % de la superficie). Les photographies aériennes montrent que bien que l'érosion éolienne ait fléchi des années 40 aux années 80, lorsque les conditions climatiques étaient relativement humides, les surfaces de sable actives se sont nettement accrues dans certaines zones après les années de sécheresse de la décennie 80. La vitesse et le style de stabilisation des dunes dépendent des conditions climatiques et de la capacité du sable et des sédiments sous-jacents à absorber et à retenir l'humidité.

Les conditions nécessaires à l'activité éolienne (un apport sédimentaire, des vents d'une force suffisante et une végétation localement éparse à absente) existaient à une échelle régionale dans le triangle de Palliser durant la déglaciation du Wisconsinien supérieur. L'accumulation éde nappes de sable et de loess a débuté dès la mise à nu des dépôts d'origine, et les dunes formées par des vents adiabatiques secs émanant de l'Inlandsis laurentidien auraient eu une orientation très différente de celle des dunes holocènes. L'éolisation marquée a pu être interrompue brièvement par une période humide juste avant 10 ka, favorisant la formation d'horizons pédologiques sur la plupart des dépôts éoliens. Au début de l'Holocène, le climat est devenu plus sec qu'il ne l'est aujourd'hui et l'activité éolienne a repris de l'ampleur. Cette période d'éolisation marquée a pu se poursuivre sans relâche jusqu'il y a quelques milliers d'années; elle a été suivie par une phase prolongée de stabilisation jusqu'à l'Holocène supérieur. Les changements de l'activité éolienne causés par les fluctuations modernes du climat ainsi que les changements des tous derniers siècles documentés par des comptes rendus historiques et des études optical dating studies, demonstrate that much of the Palliser Triangle lies near a threshold of widespread eolian activity.

The South Saskatchewan River and its three main tributaries, the Red Deer, Bow, and Oldman rivers, form the largest through-flowing drainage system in the Palliser Triangle. No major rivers have their source areas within the Palliser Triangle, and roughly 45% of the region drains internally. Recent human activity has markedly affected the region's drainage system, with all main drainages and most minor channels having been dammed or flow-regulated to some extent. Thousands of kilometres of irrigation canals, ditches, and diversions have created a complex, wholly synthetic pattern of water flow and sediment transport.

Snowfall generates about 80% of prairie stream runoff and is often the only major runoff source for small streams. The strong moisture deficit that characterizes the regional climate produces little additional runoff except when sporadic, high-intensity rainstorms occur in areas where topography and geology inhibit infiltration. Climatic variations play a major role in runoff generation, such that areas contributing runoff display great interannual variability in response to precipitation and antecedent moisture conditions.

About 70% of the mean annual discharge in major rivers is derived from the mountains and foothills to the west, whereas the majority of the sediment load is derived from inside the Palliser Triangle. This disassociation of runoff and sediment sources has a profound influence on fluvial processes. Suspended-sediment data generally show a downstream increase in sediment load, with greatest increases related to extremely high sediment yields from localized badlands. The vast majority of sediment in Palliser Triangle rivers is derived from riparian and valley-side areas in immediate proximity to river channels, with most of the land surface contributing essentially no sediment to the through-flowing rivers. This does not mean that water erosion in agricultural areas is unimportant, but rather that the sediment derived from these areas is deposited locally.

The potential effects of climate change on river systems is a contentious issue, particularly in areas like the Palliser Triangle where climate produces a narrow threshold between conditions of aggradation and degradation. Interpretation of sediment sequences and terraces as records of fluvial responses to climatic variations, although plausible, may be misleading. Terrace sequences in this region typically display overlapping aggradational and degradational phases, with few indications that terrace formation in different stream systems is

s'appuyant sur des datations optiques, montrent que le triangle de Palliser se situe en grande partie près du seuil d'une vaste activité éolienne.

La rivière Saskatchewan Sud et ses trois principaux tributaires, les rivières Red Deer, Bow et Oldman, forment le plus grand bassin versant drainant le triangle de Palliser. Aucune rivière importante n'a sa source dans le triangle de Palliser et quelque 45 % du drainage de la région est interne. Les activités anthropiques récentes ont profondément modifié le réseau hydrographique de la région, l'écoulement dans les principaux réseaux et dans la plupart des petits chenaux ayant été régularisé par des barrages ou d'autres ouvrages. Les milliers de kilomètres de canaux d'irrigation, de fossés et de canaux de dérivation ont créé un réseau complexe complètement artificiel d'écoulement de l'eau et de transport des sédiments.

Les chutes de neige produisent 80 % environ de l'écoulement fluvial dans la prairie et elles sont la principale source de l'écoulement des petits cours d'eau. Le déficit hydrique élevé qui caractérise le climat régional produit un faible écoulement additionnel sauf lorsque de fortes pluies sporadiques tombent sur des régions où la topographie et la géologie empêchent l'infiltration des eaux. Les variations climatiques jouent un rôle si important dans l'écoulement que les zones qui contribuent à l'écoulement affichent une forte variabilité interannuelle en réponse aux précipitations et aux conditions antérieures d'humidité.

Quelque 70 % du débit annuel moyen des principales rivières provient des montagnes et des foothills à l'ouest tandis que la majorité de la charge sédimentaire provient de l'intérieur du triangle de Palliser. Cette séparation entre l'écoulement et la source des sédiments influe fortement sur les processus fluviatiles. Les données sur les sédiments en suspension indiquent généralement un accroissement en aval de la charge sédimentaire, les plus fortes hausses étant liées à des apports sédimentaires considérablement élevés en provenance de badlands locales. La grand majorité des sédiments dans les cours d'eau du triangle de Palliser sont issus des zones riveraines ou des versants de vallée contigus aux chenaux fluviatiles, la quasi totalité de la surface des terres ne déversant essentiellement aucun sédiment dans les rivières qui les traversent. L'érosion par l'eau dans les régions agricoles n'est pas pour autant sans importance, mais il ressort que les sédiments provenant de ces régions sont déposés localement.

Les effets potentiels du changement climatique sur les réseaux hydrographiques est une question discutable, en particulier dans les régions comme le triangle de Palliser où le climat produit un seuil étroit entre les conditions d'alluvionnement et de désalluvionnement. L'interprétation des séquences et des terrasses sédimentaires pour y déceler les réponses fluviatiles aux variations climatiques peut être, bien que plausible, trompeuse. Les séquences sédimentaires des terrasses de cette région affichent, de façon caractéristique, des phases d'alluvionnement et de désalluvionnement synchronous. Considerable research is required to demonstrate if there has been a coherent, synchronous response of fluvial systems to past climatic variability in the Palliser Triangle.

Mass wasting processes are generally not perceived to be of major significance in landscapes of limited relief, but evidence of landsliding is ubiquitous along the many incised valleys of the Palliser Triangle, as well as along the flanks of major uplands. In fact, both the geology and geomorphic history of the Palliser Triangle strongly favour mass wasting. Slope stability is of major concern in the construction of roads crossing valleys as well as in the construction of dams within valleys. When landslides do occur, on-site economic impacts are often minimal. However, downstream impacts in water quality, and upstream impacts in modified fluvial hydrology, may be of regional significance.

Although the overriding cause of most landslides in the Palliser Triangle is the low shear strength of the Upper Cretaceous shales, it is active geomorphic and hydroclimatic conditions that actually trigger events. Slope instability is generally associated with high or perched water tables, differential groundwater pressure, and increased pressure gradients from rapid drawdown of groundwater during recession of flood water or rapid valley incision. Landslides in the Cretaceous shales commonly extend several kilometres along valley sides and cover tens of square kilometres. They usually represent complex mass movements recording several periods of activity. Slow progressive slip along planes of weakness at various elevations causes bedrock and drift to move towards the valley floor at rates ranging from centimetres to, in exceptional cases, metres per year. On plateaus, where Pleistocene deposits are thin or absent, meltwater and rain seep through loess and coarse Tertiary sediments, eventually saturating the underlying Cretaceous clays and promoting deep-seated rotational landsliding. Many apparently inactive landslides are easily reactivated by any process or event that increases the prevailing stress or decreases the frictional resistance to shear.

A major episode of landsliding is assumed to have occurred immediately following deglaciation in association with the deep, rapid incision of glacial meltwater channels. Evidence of late Holocene landsliding is also available, particularly in the Cypress Hills, where absolute and/or relative ages for 21 landslides all fall

chevauchantes où les indices de synchronisme dans la formation des terrasses dans les différents réseaux hydrographiques sont peu nombreux. Il faudra mener de vastes recherches pour déterminer si la réponse des réseaux hydrographiques aux variations climatiques anciennes dans le triangle de Palliser a été cohérente et synchrone.

Les processus de mouvement de masse ne sont généralement pas perçus comme d'une grande importance dans les paysages à faible relief, mais les glissements de terrain ont laissé des traces partout le long de nombreuses vallées encaissées du triangle de Palliser ainsi que le long des flancs des hautes terres principales. En fait, l'histoire géologique et géomorphologique du triangle de Palliser contribue à accorder de l'importance aux mouvements de masse. La stabilité des talus est une question de taille pour la construction des routes et des barrages traversant les vallées. Lorsqu'il se produit des glissements de terrain, les répercussions économiques locales sont souvent minimes. Cependant, les effets en aval de la qualité de l'eau et en amont de l'hydrologie fluviale peuvent s'étendre à une échelle régionale.

Même si la cause première de la plupart des glissements de terrain dans le triangle de Palliser est la faible résistance au cisaillement des shales du Crétacé supérieur, ce sont les conditions géomorphologiques et hydroclimatiques en cours qui les déclenchent. L'instabilité des talus est généralement associée à la présence de nappes phréatiques élevées ou perchées, à la pression exercée par l'eau souterraine et aux forts gradients de pression créés par un rabattement rapide de la nappe phréatique durant la décrue ou l'incision rapide des vallées. Les glissements de terrain dans les shales crétacés peuvent affecter plusieurs kilomètres de versants de vallée et couvrir des dizaines de kilomètres carrés. Ils représentent habituellement des mouvements de masse complexes témoignant de plusieurs périodes d'activité. Le glissement progressif observé le long de plans de faiblesse à différentes altitudes se traduit par un mouvement du substratum rocheux et des sédiments glaciaires vers le fond de la vallée à des vitesses variant de quelques centimètres à, exceptionnellement, quelques mètres par année. Sur les plateaux, là où les dépôts pléistocènes sont minces ou absentes, les eaux de fonte et de pluie s'infiltrent dans le loess et les sédiments tertiaires grossiers, finissant par saturer les argiles crétacées sous-jacentes et favoriser le déclenchement de glissements de terrain rotationnels profonds. De nombreux glissements de terrain apparemment inactifs peuvent facilement être réactivés par tout processus ou phénomène qui accentue les contraintes principales ou diminue la résistance de frottement au cisaillement.

Un épisode important de glissement de terrain lié à l'encaissement rapide de chenaux fluvioglaciaires profonds aurait suivi de près la déglaciation. Des indices de glissements de terrain datant de l'Holocène supérieur ont également été observés, particulièrement dans les collines Cypress, où les âges absolus ou relatifs de 21 glissements de terrain ne within the last 5100 years. Climate has been suggested as one factor that influences landslide activity in the Cypress Hills, as it exerts a significant influence over the regional groundwater table. A shift towards a cooler and wetter climate raises water tables, such that clay-rich strata at progressively higher elevations are subject to excess porewater and lowered resistance to shear. This increases the potential for sliding at multiple depths, with the most probable triggers identified as stream-channel shifts and extreme hydroclimatic events.

Soil redistribution in agricultural areas is the geomorphic impact of greatest concern to sustainable land management in the Palliser Triangle. The principle agents of soil erosion and transport are wind, water, and tillage. Both wind and water erosion processes are closely related to extreme climatic events, and drought is the necessary precursor to wide-spread wind erosion. Episodes of water erosion are stimulated by two hydroclimatic events: snowmelt in spring, and high-intensity rainfall throughout the snow-free period. In both cases the infiltration capacity of the soil is exceeded, generating sufficient runoff to detach and transport soil.

Fully vegetated surfaces are generally not susceptible to wind erosion, and water erosion is restricted to the most extreme forms of rill and gully erosion. Soil cultivation removes the natural protection afforded by vegetation, resulting in erosion rates two to four orders of magnitude higher on bare soil, compared with fully vegetated pasture or native grasslands. Tillage summerfallow techniques greatly increase soil surface exposure. Recently developed approaches, involving minimal tillage or herbicide suppression of weeds in the fallow year, have significantly increased the residue cover on fields, thereby promoting soil conservation.

Major wind erosion events in the Palliser Triangle are associated with prolonged dry conditions that reduce vegetation cover. Severe wind erosion is possible in all soil and landform types whenever there has been a succession of crop failures. Major snowmelt or precipitation events following a dry year also have high potential to generate significant soil redistribution. Insights into patterns of soil redistribution have emerged from recent ^{137}Cs studies in Saskatchewan. One of the most important findings is that on-site impacts of soil redistribution greatly exceed off-site impacts, insofar as net soil export from study sites is generally quite low. Although the majority of stations at each site experience mean soil

dépassent pas 5 100 ans. La climat a été proposé comme l'un des facteurs qui influent sur les glissements de terrain dans les collines Cypress puisqu'il modifie considérablement le niveau de la nappe phréatique régionale. Un déplacement vers un climat plus frais et plus humide a pour effet de faire monter le niveau de la nappe phréatique. C'est ainsi que les couches argileuses progressivement moins profondes contiennent une eau interstitielle excédentaire et ont une résistance au cisaillement plus faible. Cette situation augmente le potentiel de glissement à de multiples profondeurs, les éléments déclencheurs les plus probables étant des déplacements de chenaux fluviatiles et des événements hydroclimatiques extrêmes.

Le redistribution des sols dans les zones agricoles est l'impact géomorphologique le plus inquiétant pour les gestionnaires de l'aménagement durable des terres dans le triangle de Palliser. Les principaux agents de l'érosion et du transport des sols sont le vent, l'eau et le labourage. L'érosion par le vent et l'eau est étroitement liée à des événements climatiques extrêmes et la sécheresse est le phénomène qui précède nécessairement une érosion éolienne de grande envergure. Les épisodes d'érosion par l'eau sont accentués par deux événements hydroclimatiques : la fonte de la neige au printemps et les fortes chutes de pluie pendant toute la saison sans neige. Dans les deux cas, la capacité d'infiltration du sol est dépassée, causant un ruissellement suffisant pour détacher et transporter des sédiments.

Les surfaces recouvertes de végétation ne sont généralement pas exposées à l'érosion éolienne, et l'érosion par l'eau se limite aux formes les plus extrêmes de l'érosion en ravins et en rigoles. La culture des sols élimine la protection naturelle offerte par la végétation, provoquant des vitesses d'érosion de deux à quatre ordres de grandeur plus élevées sur le sol nu que sur les pâturages complètement cultivés ou les prairies naturelles. Les techniques de mise en jachère des terres labourées exposent davantage la surface des sols à l'érosion. Les méthodes récentes, par lesquelles le labourage est minime et l'épandage d'herbicides est interrompue pendant l'année de jachère, se sont traduites par un épaississement significatif des résidus sur les champs, d'où une protection accrue des sols.

Les principaux phénomènes d'érosion éolienne dans le triangle de Palliser sont associés à une prolongation des conditions de sécheresse, ce qui a pour effet de réduire le couvert végétal. L'érosion éolienne peut être importante dans tous les types de sols et de modelé où il y a eu une succession de récoltes déficitaires. Les principaux événements liés à la fonte nivale ou aux précipitations après une saison sèche risquent fort d'entraîner une redistribution significative des sols. Des études récentes basées sur l'isotope ^{137}Cs en Saskatchewan ont permis d'approfondir les modes de redistribution des sols. Selon l'une des conclusions les plus importantes qui ont été tirées, les répercussions sur place de la redistribution des sols dépassent considérablement les répercussions à l'extérieur du losses in excess of 10 t·ha^{-1}·a^{-1}, most of this sediment is redeposited within the confines of the study site. Landscape-scale models of soil redistribution must take into account within-field deposition if a realistic sediment budget for a given landscape is to be developed.

Uncertainties concerning the nature and magnitude of future climate change, as well as the spatial complexity of Palliser Triangle landscapes, make land-use-scale predictions of geomorphic impacts untenable. However, by adopting a scenario-consequence approach, it is possible to identify a range of possible outcomes for landscape elements that exhibit critical vulnerabilities under specific scenarios. Identification of possible outcomes sets the stage for proactive land management, facilitating rapid adaptation or implementation of particular elements when reliable, long-term, regional climatic projections are available, or when trends can be clearly defined through monitoring.

Four very simple climate scenarios are considered in this report: I) warmer and drier; II) warmer and wetter; III) cooler and wetter; and IV) cooler and drier. Greatest focus is placed on scenario I, which is deemed the most probable climatic future for the southern prairie region. It is also the scenario that exerts the greatest impacts on environmental, social, and economic systems. The smallest impacts are associated with scenarios II and IV, as precipitation and temperature changes potentially offset each other with respect to regional water balance.

The greatest impacts associated with a climate that is warmer and drier than at present are indirect responses to vegetation changes. Heightened aridity and increased drought reduce vegetation cover, thereby increasing potential sediment supply to all geomorphic systems. The mid-Holocene probably serves as the best analogue for this scenario, although similar conditions may have prevailed as recently as the Medieval Warm Period (ca. 900-1200 AD). Under these conditions, large-scale mobilization of presently stabilized sand dunes could potentially occur in a decade. Large dunes, in which moisture is almost entirely dependent on direct recharge by precipitation, would activate more rapidly than smaller dunes, where groundwater may contribute directly to moisture content. Although dune activity would increase markedly, dune morphology would continue to be dominated by parabolic, rather than barchan, features. More rapid reactivation of stabilized sand

site, étant donné que l'exportation nette de sol à partir des sites à l'étude est généralement très faible. Bien que la majorité des stations réparties entre tous les sites subissent des pertes moyennes de sol de 10 t·ha^{-1}·a^{-1}, la grande partie de ces sédiments est redéposée à l'intérieur des limites du site à l'étude. Les modèles de redistribution des sols à l'échelle d'un paysage doivent tenir compte du dépôt intérieur si l'on projette d'élaborer un bilan réaliste des sédiments dans un paysage donné.

Les incertitudes relativement à la nature et à l'ampleur du changement climatique futur ainsi que la complexité spatiale des paysages du triangle de Palliser rendent impossibles la prévision des répercussions géomorphologiques dans un contexte d'aménagement des terres. Cependant, en adoptant une approche axée sur les conséquences des scénarios, il est possible de faire ressortir un éventail des résultats possibles pour les éléments du paysage qui présentent des vulnérabilités critiques selon certains scénarios. L'identification des résultats possibles marque le pas d'une gestion proactive des terres, accélérant l'adaptation ou l'application d'éléments particuliers lorsqu'on peut s'appuyer sur des prévisions climatiques régionales fiables à long terme ou lorsqu'on peut tracer clairement les tendances par le biais d'un suivi.

Dans le présent rapport, nous nous pencherons sur quatre scénarios climatiques très simples : I) conditions plus chaudes et plus sèches; II) conditions plus chaudes et plus humides; III) conditions plus froides et plus humides; et (V) conditions plus froides et plus sèches. Nous mettrons l'accent sur le premier scénario que l'on considère le plus probable dans les prairies méridionales. Ce scénario produit en outre les répercussions les plus percutantes sur les systèmes environnementaux, sociaux et économiques. Les répercussions les plus ténues sont associées aux scénarios II et IV, car les changements qui seraient observés dans les précipitations et la température pourraient se contrebalancer l'un l'autre par rapport au bilan hydrique régional.

Les répercussions les plus lourdes associées à un climat plus chaud et plus sec qu'aujourd'hui découlent indirectement de changements dans la végétation. Une aridité amplifiée et une sécheresse accrue réduisent le couvert végétal, d'où un apport potentiellement plus élevé de sédiments à tous les systèmes géomorphologiques. L'Holocène moyen est probablement la période qui correspond le mieux à ce scénario, bien que des conditions semblables aient pu exister aussi récemment que pendant la période de réchauffement médiéval (vers 900-1200 AD). Dans de telles conditions, la mobilisation à grande échelle de dunes de sable actuellement stabilisées pourrait avoir lieu dans une décennie. Les grandes dunes, dans lesquelles l'humidité dépend quasi entièrement de la réalimentation par les précipitations, se remettraient en mouvement plus rapidement que les plus petites dunes, là où les eaux souterraines peuvent contribuer directement à la teneur en humidité. Malgré le fait que l'activité dunaire augmenterait de façon marquée, la morphologie des dunes ne cesserait pas d'être surtout parabolique plutôt qu'en croissant. La dunes is only possible through destructive human or animal activity, and could occur without additional climatic stresses.

Fluvial responses to warmer and drier conditions are especially difficult to evaluate given that the majority of water in through-flowing drainages is derived from the Rocky Mountains and foothills, regions that may experience climatic impacts unlike those on the southern prairies. In theory, the greatest levels of change in discharge and sediment yields are expected in areas, like the Palliser Triangle, that are transitional between humid and semiarid climates. However, as the majority of the sediment load entering through-flowing rivers is derived from relatively small areas, it is expected that decreases in basin-wide precipitation will cause little variation in the already high badland erosion rates.

A change in the climate to warmer and drier conditions should generally favour slope stability, since such conditions would deplete groundwater and stream flow, two principal controls of slope failure. However, since a drier climate will undoubtedly increase irrigation demands, slope instability related to excess irrigation could increase locally. Also, if climate change is associated with an increase in the frequency of extreme hydroclimatic events, large storms and floods could generate landslides.

The warmer/drier scenario also has great implications for soil redistribution. The closest historical analogue is the 1930s, when prevailing conditions led to widespread soil destabilization. A return of such conditions would presumably lead to lower crop-residue inputs, higher incidence of fallowing and, in the most extreme cases, farm abandonment. Crop cover in a drought year, and residue cover on fallow fields in the year following a drought, are greatly reduced, leaving the soil surface much more susceptible to wind erosion in the following spring or summer. Moreover, the absence of residual cover would also significantly increase the impact of high-intensity rainfall events. Despite regional differences in soil characteristics, it is fair to conclude that the impacts of this scenario on soil erosion in all areas would likely be severe.

réactivation de dunes de sable stabilisées ne serait plus rapide que si les activités humaines ou animales étaient destructrices, ce qui pourrait se produire sans contraintes climatiques additionnelles.

Il est difficile d'évaluer la réponse des cours d'eau à des conditions plus chaudes et plus sèches étant donné que la grande partie de l'eau qui circule dans les réseaux traversiers provient des Rocheuses et des foothills, régions qui pourraient connaître des effets climatiques différents de ceux prévus dans les prairies méridionales. En théorie, on s'attend à ce que les changements dans le débit et les apports sédimentaires soient plus importants dans les régions qui, comme le triangle de Palliser, se caractérisent par un climat de transition d'humide à semi-aride. Toutefois, comme la charge sédimentaire qui pénètre dans les cours d'eau traversiers provient surtout de zones de faible étendue, on prévoit que la diminution des précipitations à l'échelle du bassin modifiera peu les taux d'érosion déjà élevés que l'on observe dans les badlands.

Un réchauffement et un assèchement du climat devraient favoriser la stabilité des talus, étant donné que les eaux souterraines et les cours d'eau seraient moins bien alimentés et que ce sont là deux facteurs principaux de rupture de pente. Cependant, comme un assèchement du climat accentuerait sans doute les besoins d'irrigation, il se pourrait que l'instabilité des talus liée à une irrigation excessive puisse augmenter localement. De plus, si le changement était associé à une augmentation de la fréquence des événements hydroclimatiques extrêmes, les grosses tempêtes et les crues pourraient déclencher des glissements de terrain.

Le scénario du climat plus chaud et plus sec a des conséquences importantes sur la redistribution des sols. La situation se rapprochant le plus de ce scénario remonte aux années 30, période pendant laquelle les conditions ont provoqué une déstabilisation des sols à grande échelle. Le retour de telles conditions abaisserait probablement les apports de résidus dus aux cultures, augmenterait l'incidence de la mise en jachère des terres et, dans les cas extrêmes, causerait l'abandon des fermes. On observe une réduction considérable de la superficie cultivée pendant une année de sécheresse et de l'épaisseur des résidus sur les jachères pendant l'année suivant une sécheresse, laissant la surface du sol davantage exposée à l'érosion éolienne au cours du printemps et de l'été suivants. De surcroît, l'absence d'une couverture de résidus augmenterait sensiblement l'impact des chutes de pluie de forte intensité. Malgré des différences régionales dans les caractéristiques des sols, on peut à juste titre conclure que les incidences de ce scénario sur l'érosion des sols dans toutes les régions porteraient à conséquence.

INTRODUCTION

D.S. Lemmen, R.E. Vance, and I.A. Campbell

Overview

In the nineteenth century, the southern Interior Plains of western Canada (Fig. 1) were viewed as a continuation of the Great American Desert; a vast expanse of sparsely vegetated prairie extending from the Mississippi River to the Cordillera. The report of the 1857-1860 British North American Exploring Expedition, led by Captain John Palliser, identified a region, crudely triangular, that the expedition regarded as comparatively useless for agricultural settlement (Spry, 1968). Extending along the 49th parallel between 100° and 114°W longitude, with its apex at about 52°N latitude, the Palliser Triangle covers more than 200 000 km^2 of what is now southern Saskatchewan, southeastern Alberta and extreme southwestern Manitoba (Fig. 2). The past century has proven this same region to be one of the world's most productive agricultural areas, and in many years it accounts for more than half of Canada's agricultural production (Science Council of Canada, 1986). Nonetheless, the social, economic, and biophysical impacts of periodic drought, particularly in the 1930s and 1980s, serve as a vivid reminder of Captain Palliser's ominous assessment.

Palliser's conclusions become even more ominous in light of projections that increased concentrations of atmospheric greenhouse gases (carbon dioxide, methane and nitrous oxide, among others) will result in global warming, a trend that may already be detectable in the recent climate record (Intragovernmental Panel on Climate Change, 1996). General Circulation Model (GCM) simulations suggest that the entire northern Great Plains will be subjected to more frequent droughts early in the next century (e.g. Karl and Heim, 1991). This scenario has been underscored by a recent effort to scale down GCM output to examine the implications of global climate change for the Canadian prairie region, that concluded "the potential for higher summer temperatures without the mitigating influence of increased precipitation can be expected to enhance soil moisture deficits in the region" (Saunders and Byrne, 1994, p. 639). Because of these projections and the fact that most economic activities in the region are climate dependent to some degree (Wheaton et al. 1992), the Geological Survey of Canada selected the Palliser Triangle as an Integrated Research and Monitoring Area (IRMA). The goal of the IRMA is to assess at a regional level the geomorphic effects of future environmental change based largely upon an improved understanding of Holocene climatic variability and the associated responses of geomorphic systems (Lemmen et al., 1993).

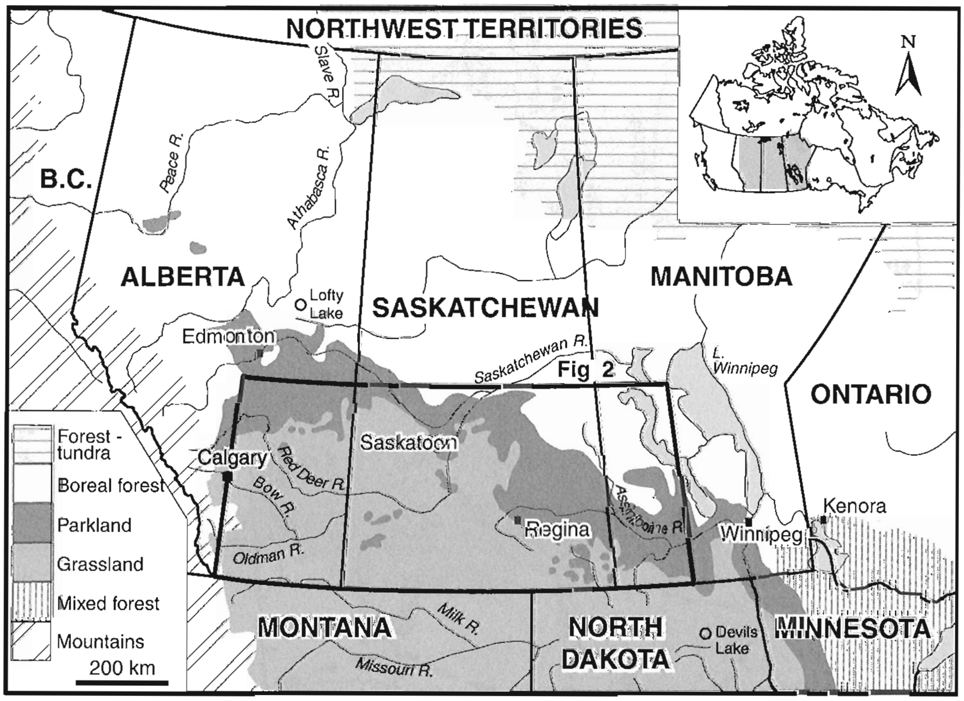


Figure 1. *Ecozones and major drainages of the prairie provinces and surrounding regions. The Palliser Triangle occupies much of the grassland ecozone (see Fig. 2). Modified from Vance et al. (1995).*

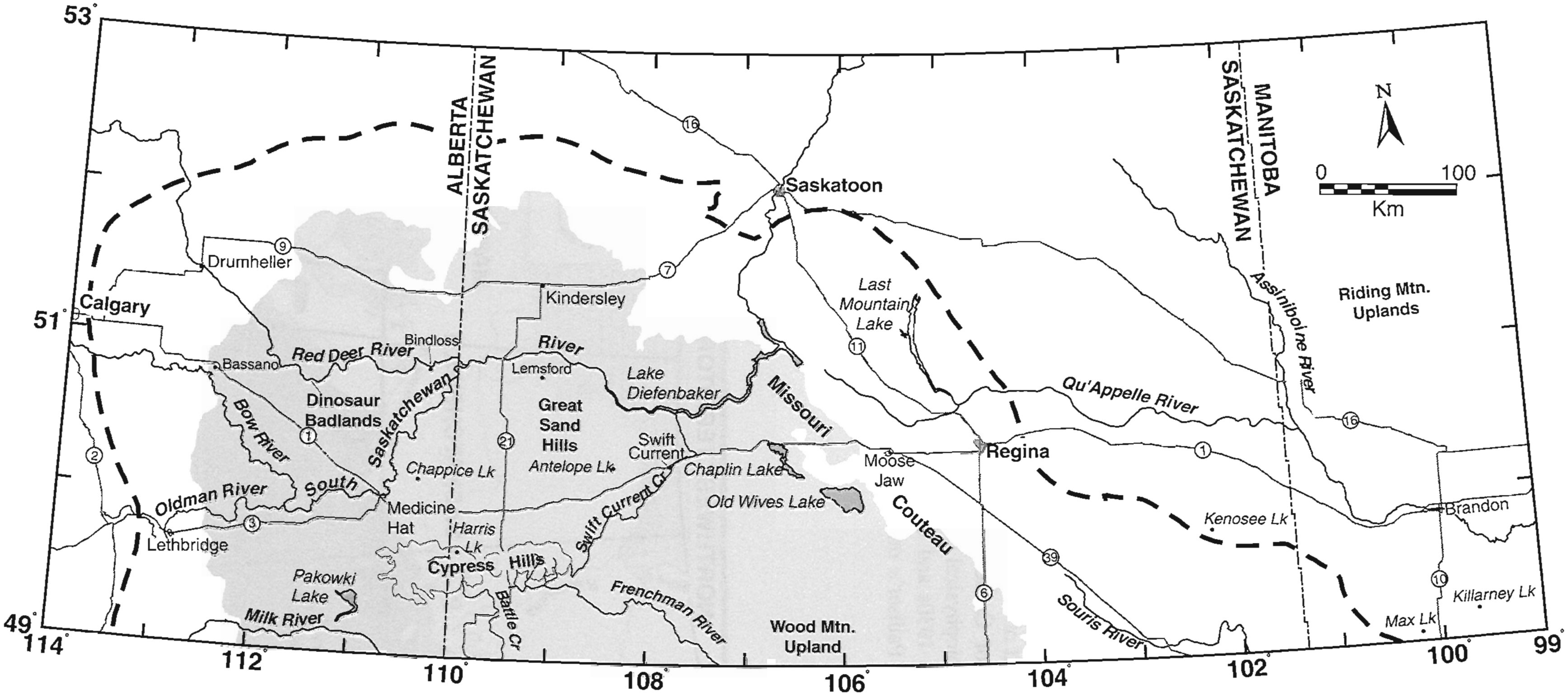


Figure 2. The Palliser Triangle (dashed line) as defined by Capt. John Palliser following his survey of the region from 1857-1960. The Brown Chernozemic Soil Zone (shaded; from Canada Soil Inventory, 1987a, b) represents an integration of climate, vegetation, and geology during the Holocene, and is used in this paper as a working definition of the Palliser Triangle. Most subsequent maps depict this region only. Major highways and cities are shown for reference, all other place names are referred to in the text.

Geomorphic systems consist of interacting processes and landforms that together form a landscape complex. Application of systems theory to geomorphology has been developed over the past several decades in a series of benchmark papers (e.g. Chorley, 1962; Schumm and Lichty, 1965; Schumm, 1977a) and the concepts have been thoroughly reviewed in many text books (e.g. Chorley and Kennedy, 1971; Chorley et al., 1984). Spatial and temporal scale are critical characteristics of all geomorphic systems. Although the nature of any geomorphic system is the product of processes operating at all scales, at any one scale certain processes are dominant while others can essentially be ignored (deBoer, 1992). In this report, the term 'geomorphic systems' is used in a general sense to examine landscape processes and impacts related to the through-flow of mass and energy at a regional scale. The objective is to outline the existing pattern of geomorphic activity in terms of its eolian, fluvial, slope, and soil-redistribution components, in order to better understand how climate-induced changes to these systems could affect human activities. Defining spatial variations that exist today provides a baseline set of conditions against which the possible effects of future changes can be assessed. The spatial scale of interest in this report ranges from mesoscale (e.g. hillslope, dune field) to macroscale (e.g. drainage basin, region). The temporal scale is more narrowly focused (mesoscale; years to decades), dictated by the objective of examining impacts on human activities. As a result, small-scale processes (e.g. initiation of particle transport) are not emphasized in this report.

Climate is a critical, extrinsic, independent variable in most geomorphic systems. The potential geomorphic impacts of future climate change and their relevance to issues of sustainability represent both a challenge and an opportunity to geomorphologists (Jones, 1995). As a literature review, this report provides a basis for formulating generalized statements about the probable geomorphic impacts of climate change, which are presented in "Potential Effects of Future Climate Change on Geomorphic Systems" . These statements alone, however, do not provide all the information necessary to predict landscape response at a scale applicable to land management. This is a far more difficult challenge that must take into account the inherent complexity of geomorphic systems, particularly concepts such as thresholds and response times (e.g. Schumm, 1977a), and the fact that this complexity increases with increasing spatial scale (cf. Brunsden, 1993). A second factor limiting our ability to predict future impacts is the uncertainties concerning the nature of future climate change, particularly at regional scales where confidence in GCM projections remains low (Intragovernmental Panel on Climate Change, 1996). Uncertainties are greatest with respect to critical hydrological parameters, such as rainfall seasonality, intensity, and storminess, all of which strongly influence geomorphic processes. Finally, and perhaps most importantly, is the potential dominance of human over climatic factors in determining the nature of geomorphic response. Although it is likely that there will be significant geomorphic impacts associated with climate change, in most cases they are unlikely to be catastrophic unless accompanied by poor land-management practices (cf. Jones, 1995).

The Palliser Triangle

Implicit in Captain Palliser's writings is that the 'Triangle' is a climatically, rather than geographically, defined region. Since the climate of this region is highly variable both in space and time (see "Climate, Vegetation and Soils"), the boundaries of the 'Triangle' itself should also be considered variable with time. The latter half of the 1980s reinforced the fact that climatic variability is a fact of life in the Palliser Triangle. Globally, it was the warmest five-year period of the meteorological record (Kerr, 1996). The year 1988 was particularly warm and dry in the Palliser Triangle: mean annual temperatures were 2-4°C above the thirty-year normal and precipitation was, in some areas, less than half the 1950-1980 average (Wheaton and Arthur, 1989). These conditions produced severe regional drought, reminiscent of the 1930s and late 1850s. Had Palliser's expedition traversed the region during intervening years, it is likely that the 'Triangle' would have been given a somewhat different geographic definition.

For the purposes of this report, the Palliser Triangle is considered synonymous with the Brown Chernozemic Soil Group (Fig. 2), since soil characteristics are an integration of climatic variability, vegetation, and parent material over time scales of millennia. This soil group forms a readily definable area of about 125 000 km^2 in the heart of Captain Palliser's triangle and represents the driest, and hence most climatically sensitive, portion of the region. Even using this more restricted definition, the Palliser Triangle embodies a great variety of landscapes, including sparsely vegetated surfaces, forested bedrock uplands, active sand dunes, thin, often highly saline soils, and localized examples of intensively eroded and mass-movement-dominated landscapes.

Human impacts

The effects of climatic change on geomorphic systems in the Palliser Triangle is principally of interest in determining how these changes affect human activities, most notably agriculture. It raises fundamental issues of 'regional sustainability', which may be defined in general terms as development strategies that meet "the needs of the present without compromising the ability of future generations to meet their own needs" (World Council on Environment and Development, 1987). Sustainability issues on the Great Plains, which involve a number social, economic, and environmental considerations from agricultural production, land

and water resources, human and community resources, biological resources and biodiversity, to integrated resource management, are summarized in Wilhite and Wood (1995).

It can be argued that many activities on the Great Plains, including the Palliser Triangle, have not been truly sustainable since the time of European settlement. World demand for Canadian wheat and an influx of prairie settlers in the early twentieth century resulted in the wholesale ploughing of grasslands. Favourable climatic conditions and high soil quality in the early 1900s created a false sense of security in the agricultural community. However, a series of droughts through the 1920s and 1930s that featured extensive wind erosion of prairie soils stimulated economic, social, and political repercussions that remain imprinted on the landscape and in the minds of its inhabitants. The rural depopulation that has characterized much of the region since the 1920s is the most striking evidence of sporadic adjustments toward economic sustainability (e.g. Duncan et al., 1995). Other important moves toward increased environmental sustainability include a 27% decrease in the amount of land left in summer fallow over the past three decades and the conversion of 1.2×10^6 acres of land from annual cropland to permanent cover as range lands since 1989 (Hill and Vaisey, 1995). Both of these trends dramatically reduce regional susceptibility to soil erosion.

Despite these ongoing changes, impacts of the severe drought of 1988 (including wind erosion, dust storms, and a 29% drop in wheat production; Wheaton and Arthur, 1989) once again raised the spectre of the human impacts related to environmental deterioration driven by climate. Human activities in any region evolve to operate within a range of conditions (coping range; e.g. Smit, 1995) that, in the absence of other external forces, should reflect climatic variability (Fig. 3). The continued vulnerability of social, economic, and environmental systems to the inherent climatic variability of the Palliser Triangle suggests that the coping range for this region is too narrow at present. In the agricultural sector, numerous government economic programs have traditionally insulated the industry against the impacts of extreme climatic events (Fig. 3), promoting development of a narrow coping range. Additionally, it is possible that the relatively short duration of agricultural activity in this region is inadequate to define, and hence allow adaptation to, the complete range of climatic variability. Regardless of the cause, it is reason for concern since human activities best adapted to climatic variability will be better positioned to adapt to future climate change (Smit, 1995).

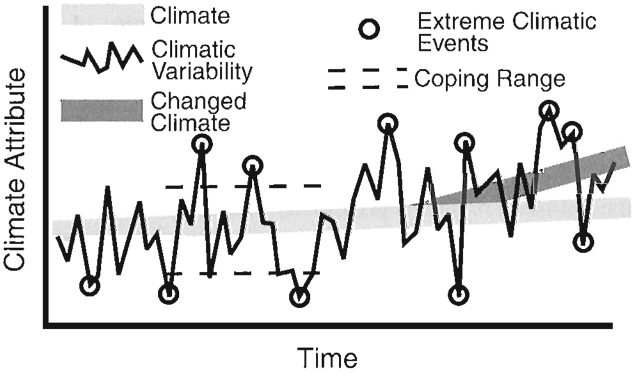


Figure 3. *Schematic illustration of the concept of coping ranges within the context of climatic variability. Note that the coping range must be expanded or adjusted to adapt to climate change (modified from Smit, 1995).*

Geomorphic impacts

Geomorphic response to global climate change should be particularly evident in landscapes such as the Palliser Triangle which exist at, or close to, threshold conditions. Subhumid and semiarid regions of the world contain prime examples of such delicately balanced, highly dynamic, geomorphic systems (e.g. Bull, 1991). Such terrains are sensitive to even relatively minor changes in climate, whether induced by short-term variability (seasonal, annual, or decadal), or long-term climatic shifts associated with global change. In an effort to systematically examine possible landscape responses to climate change, this report includes an extensive review of literature concerning geomorphic systems in the Palliser Triangle. Background on the physical environment of the Palliser Triangle is presented in the two sections following the introduction: "Geologic Setting" and "Climate, Vegetation and Soils". The four major sections of this report are each devoted to a major geomorphic system:

1. "Eolian Processes and Landforms" examines the most sensitive, and likely the most predictable, of these geomorphic systems. Emphasis is placed on sand dunes, since the Palliser Triangle contains the largest area of active sand dunes in southern Canada. Eolian activity serves to limit grazing capacities in dune regions, and has other direct impacts on human activities (e.g. dune migration across transportation corridors). However, the greatest value of understanding and monitoring eolian processes may be that they serve as a sensitive measure of instability in larger geomorphic systems (Vance and Wolfe, 1996). Eolian processes are an extremely important component of soil erosion, as discussed in "Soil Redistribution".
2. "The Fluvial System" of the Palliser Triangle has two important attributes that contribute to its distinctive nature. First, about 70% of mean annual river discharge is derived from outside the region, whereas the majority of the sediment load is derived from inside the Palliser Triangle. Second, roughly 45% of the region drains internally, contributing neither water nor sediment to the through-flowing rivers. Water and soil are two of the

most important natural resources with respect to economic sustainability. At present, water rights along the major drainages have been fully allocated, such that any significant changes in discharge or water quality will have major implications for agriculture (Byrne et al., 1989; Cohen et al., 1992).

3. "Mass Wasting Processes" are generally not perceived to be of major significance in landscapes of limited relief, but landsliding is ubiquitous along the many incised valleys of the Palliser Triangle as well as along flanks of major uplands. Slope stability is of major concern in the construction of roads crossing valleys as well as in the construction of dams within valleys. When landslides do occur, on-site economic impacts may be minimal; however, impacts downstream in water quality, and upstream in modified fluvial hydrology, can be of regional significance (Sauchyn and Lemmen, 1996).
4. "Soil Redistribution" is likely the most important concern with respect to the potential geomorphic impacts of climate change. The 'system' as discussed in this report would represent a higher hierarchical level (cf. Trudgill, 1976) than the eolian, fluvial, and mass wasting systems described previously. Soil redistribution is an integration of the processes associated with all three of these systems as well as with tillage, an extremely important anthropogenic process. Discussion here focuses on the patterns of soil redistribution and the importance of land-use practices. If future climate changes were to result in wholesale crop failure for several consecutive years, the long-term impacts in terms of soil erosion will be extremely significant.

The final section of this report is a qualitative discussion of the potential impacts that four climate-change scenarios would exert on each geomorphic system and related human activities. These general statements should not be interpreted as an attempt to predict landscape impacts at a land-management scale, which is likely impossible at this time. However, ongoing Palliser Triangle IRMA research is focused on identifying elements of the landscape that are most likely to be severely affected by climate. This involves analysis of landscape sensitivity (Brunsden and Thornes, 1979), a concept that remains poorly applied at the regional scale. Identification of the most sensitive landscape elements (most labile; Trudgill, 1976) allows these to be considered for special land-management practices or policies that may not necessarily apply to large parts of a region where landscapes are less sensitive. Mapping and modelling provide the primary basis for landscape sensitivity analysis, but important information can also be derived from the study of past geomorphic responses to climate change (cf. Allison and Thomas, 1993). All of these approaches are being utilized for the Palliser Triangle IRMA (e.g. Ambrosi, 1995; Lemmen et al. 1996), building upon the basic understanding of geomorphic systems presented in this report.

GEOLOGICAL SETTING

D.S. Lemmen

Bedrock geology

The Palliser Triangle lies within the southern reaches of the Western Canada Sedimentary Basin, a thick wedge of Phanerozoic strata overlying Precambrian basement rock. The geological evolution of the basin has recently been summarized by Leckie and Smith (1993), and in atlas form by Mossop and Shetsen (1994). The Brown Chernozemic Soil Zone, used in this paper as a working definition of the Palliser Triangle (see "Introduction"), is underlain by generally poorly consolidated clastic sedimentary rocks (both marine and terrestrial) of Late Cretaceous to Miocene age (Fig. 4A). These sediments were deposited during a series of transgressive/regressive cycles within the marine basin associated with uplift in the Rocky Mountains to the west (Laramide Orogeny), as well as with post-tectonic isostatic adjustments during the Tertiary (Leckie and Smith, 1993). The regional stratigraphic nomenclature is summarized in Figure 5, while more detailed descriptions and references are in Dawson et al. (1994).

Although Pleistocene deposits mantle most of the region (see "Surficial materials", below), the underlying bedrock unit with the greatest areal extent (subcrop) is the Upper Cretaceous Bearpaw Formation (marine shales, siltstone, and lesser sandstone; Fig. 4A). Minor concretionary ironstones and bentonitic beds (primarily highly expansive montmorillonite) within this formation have considerable local geomorphic significance, particularly in badland regions (see "Surficial materials", below, and "The Fluvial System") and along major meltwater channels (see "Mass Wasting Processes"). Upper Cretaceous strata (Whitemud and Battle formations) underlying Tertiary sandstone and conglomerates in the Cypress Hills and Wood Mountain Upland (Fig. 4A) also greatly influence modern geomorphic processes by promoting deep-seated landsliding (see "Mass Wasting Processes").

Regional degradation, mainly the result of regional tectonic and isostatic uplift from the Eocene through to the Pleistocene, removed more than 900 m of sediment in some areas of the Interior Plains (Leckie and Smith, 1993) forming much of the modern large-scale physiography. The Oligocene Cypress Hills Formation was produced during a period of renewed fluvial deposition in response to Eocene igneous intrusions that formed the Sweetgrass Hills, and Bearpaw and Highwood mountains of northern Montana (Leckie and Cheel, 1989). Fluvial reworking of sediments continued throughout the Late Tertiary, depositing the Wood Mountain Formation (Miocene) as well as preglacial sand and gravel (Pliocene to Pleistocene Saskatchewan sands and gravels and Empress Formation) in valleys that are now commonly buried by glaciogenic deposits.

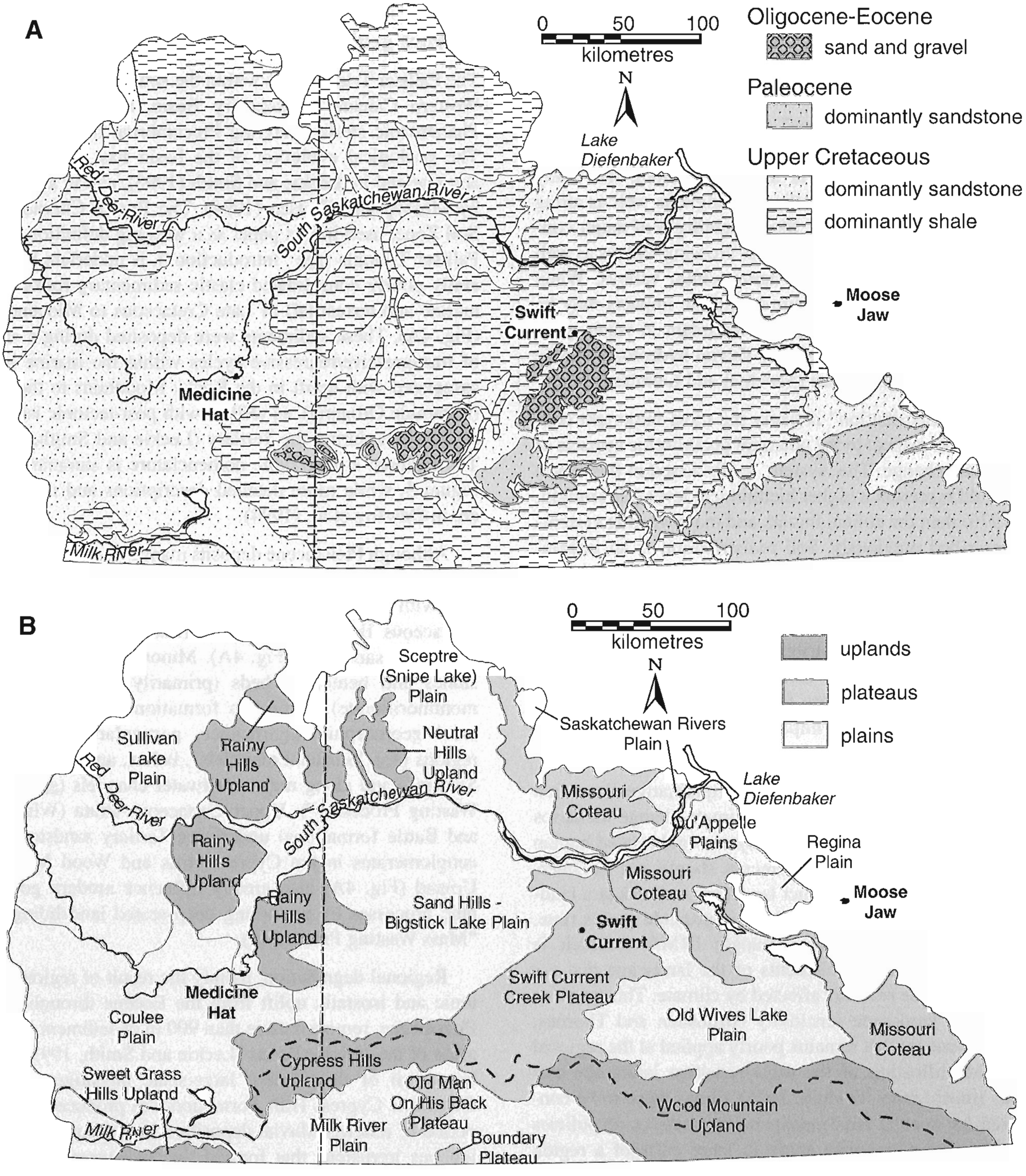


*Figure 4. A) Simplified bedrock geology depicting ages and dominant rock types. Compiled from Whitaker and Pearson (1972) and Green (1972). **B)** Physiographic subdivisions of the southern portion of the Alberta Plain. Compiled and modified from Acton et al. (1960), Pettapiece (1986), and Klassen (1992a). Dashed line denotes continental divide separating Hudson Bay and Gulf of Mexico drainages, although large portions of the region drain internally (see Table 3).*

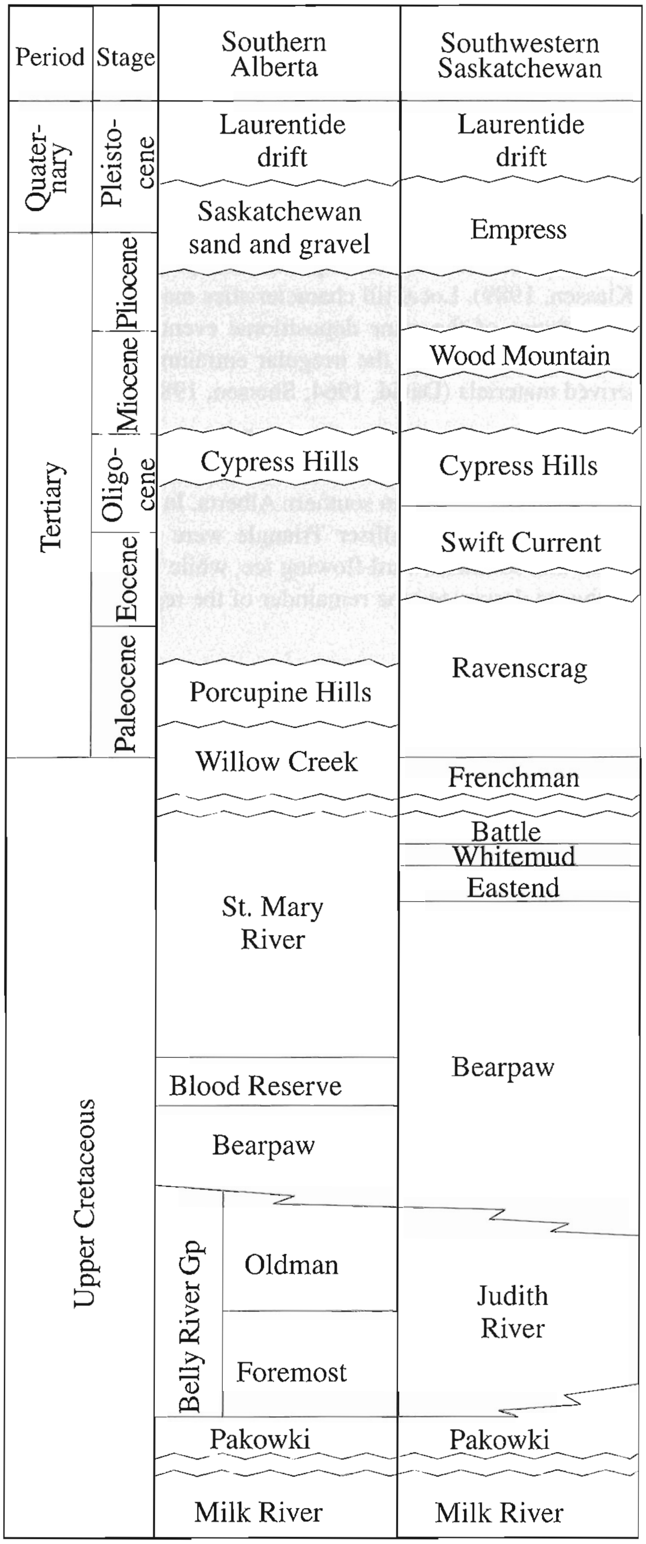


Figure 5. Regional stratigraphic nomenclature. Modified from Dawson et al. (1994).

Physiography

The Palliser Triangle (as defined previously) lies within the Alberta Division of the Interior Plains Region (Bostock, 1970), and ranges in elevation from 557 m a.s.l. (Lake Diefenbaker) to 1465 m a.s.l. (West Block of the Cypress Hills). It includes part of the continental drainage divide (Fig. 4B), with runoff from the extreme southern part of the region flowing to the Gulf of Mexico via the Milk River and its tributaries. The remaining through-flowing rivers drain northeast to Hudson Bay, although large parts of the region drain internally (see "The Fluvial System")

Major physiographic features of the Palliser Triangle are bedrock controlled, reflecting Tertiary degradation (Alden, 1932; Klassen, 1989). The eastern boundary of the region is delimited in large part by the Missouri Coteau (Fig. 4B), a bedrock escarpment overlain by extensive ice-thrust features and hummocky moraine that rises 50 m to more than 250 m above the plains to the east, forming the 'second prairie step' (Klassen, 1989; the first 'step' is the Manitoba Escarpment to the east). Another marked topographic step occurs along the margins of the Cypress Hills and Wood Mountain Upland (Fig. 4B), corresponding to the edge of Tertiary beds overlying weak Cretaceous bedrock (Klassen, 1989). Less prominent plateaus and uplands within the plains commonly represent interfluves between Tertiary drainages.

Superimposed upon bedrock-controlled physiographic elements are smaller scale features related to Pleistocene glaciation. Most of the region, with the exception of the highest parts of the Cypress Hills and Wood Mountain Upland, has been glaciated (Klassen, 1989). Drift is generally thin (<30 m), although locally may exceed 150 m, with the greatest thicknesses found in buried valleys and belts of stagnation moraine (Fenton et al., 1994). Relatively flat plains, formerly covered by glacial lakes, are the most extensive features of the region. One of the major impacts of glaciation was the disruption of pre-existing drainage patterns, as the Laurentide Ice Sheet diverted rivers and filled preglacial valleys (Klassen, 1989). Most integrated drainages in the region today originated as part of deglacial meltwater systems. During deglaciation, the Laurentide Ice Sheet blocked regional drainage to the northeast, forming a series of proglacial lakes that often drained catastrophically as continued ice retreat opened new drainage outlets. This rapid shifting of drainage channels, combined with the enormous volumes of water stored in short-lived glacial lakes, produced deeply incised (30-100 m), steep-walled meltwater channels that often form the only significant relief over large areas of the plains (e.g. Kehew and Teller, 1994).

Surficial materials

The majority of surficial materials and much of the local topography were produced by glaciation (Fig. 6, back pocket). Although a full understanding of the distribution of glacial sediments requires detailed reconstruction of ice retreat from the last glacial maximum, it is beyond the scope of this report (see Christiansen (1979) and Klassen (1989) for a regional overview). The following section emphasizes the nature, rather than the distribution, of surficial materials.

Bedrock

Extensive areas of bedrock outcrop are mainly restricted to unglaciated portions of the Cypress Hills and Wood Mountain Upland, as well as adjacent glaciated slopes that are mantled by reworked bedrock and rare erratic boulders (Klassen, 1992a) (Fig. 6). All of these areas are underlain by Tertiary sand and gravel of the Ravenscrag, Cypress Hills, and Wood Mountain formations. Surface features, including well developed pediments, reflect millions of years of subaerial erosion under a dry climate (e.g. Klassen, 1992a), and stand in marked contrast to the surrounding, comparatively young, glaciated landscape. Although bedrock outcrops are common in incised valleys (see "Valley complex", below), these exposures are generally limited in areal extent. Where significant areas of weak, Upper Cretaceous rocks have been exposed by postglacial erosion, Holocene fluvial and slope processes commonly produce spectacular badlands (e.g. Dinosaur, Onefour, Big Muddy, and Killdeer badlands). On the plains, minor bedrock exposures are found where drift is extremely thin (Shetsen, 1987; Klassen, 1992a).

Till

Till, used here to refer to glacial diamictons that are either undisturbed or have only been minimally reworked by fluvial or lacustrine processes, mantles more than 55% of the Palliser Triangle. For the purpose of Figure 6, tills have been divided into two broad classes based on surface morphology: I) till plains – relatively flat to gently rolling terrain that commonly mirrors the underlying bedrock surface; and II) hummocky moraine – irregular surfaces with greater local relief (about 5-30 m) that are not bedrock controlled. Hummocky moraine is generally associated with areas of ice stagnation (stagnation moraine of Shetsen (1987)), although it also includes widespread ice-thrust features (Aber, 1993).

Although data on surface till composition has not been compiled in detail for most of the Palliser Triangle, existing information suggests a striking homogeneity, with the matrix composed of roughly equal proportions of clay, silt, and sand, and carbonate content ranging from 5-15% (Klassen, 1989, 1992a). This uniformity, in turn, reflects the relatively homogeneous nature of the Bearpaw Formation that underlies most glaciated portions of the study area (Fig.4A). Montmorillonite imparts a low permeability and high plasticity to the tills, which tend to become extremely sticky when wet (Scott, 1989). Gravel clasts are mainly composed of Shield lithologies and Paleozoic carbonates, derived far to the north and northeast, as well as Tertiary carbonates and quartzites that were entrained by the ice sheet as it advanced across uplands and preglacial valleys (Klassen, 1989). Local till characteristics may relate to different facies of the same depositional event (e.g. Klassen and Vreeken, 1987) or the irregular entrainment of locally derived materials (David, 1964; Shetsen, 1984).

Pebble lithology has proven an effective means of determining till provenance, allowing Shetsen (1984) to identify three distinct ice lobes in southern Alberta. In general, western portions of the Palliser Triangle were influenced by south- and southeastward-flowing ice, while ice flow to the southwest dominated the remainder of the region.

Glaciofluvial deposits

Glaciofluvial deposits occur sporadically across most of the Palliser Triangle, but individual occurrences tend to be of limited areal extent and are therefore not well represented in Figure 6 . It should also be noted that the distribution of these sediments in Figure 6 may be somewhat misleading, as it likely reflects methodological differences used to compile the source maps as much as geological differences. Caution must therefore be employed when interpreting apparent regional patterns, such as the occurrence of relatively large units in the eastern part of the map, as well as the apparent absence of glaciofluvial deposits elsewhere.

Glaciofluvial deposits are typically composed of moderately to well sorted, stratified sand and gravel in the form of outwash plains, fans, deltas, and eskers. They are commonly associated with extensive meltwater channel systems which are also underlain by glaciofluvial sediment (see "Valley complex", below). Gravel lithologies tend to be dominantly Shield clasts and quartzites. In some instances weak local rock types (e.g. shale) can dominate, indicating a very limited distance of transport. The finer facies of these deposits (particularly deltaic sediments) have commonly been reworked by eolian processes (see "Eolian deposits", below).

Lacustrine and glaciolacustrine sediments

During retreat of the Laurentide Ice Sheet, regional drainage to the northwest was blocked, creating a series of ice-dammed glacial lakes (Kehew and Teller, 1994). As a result, approximately 25% of the region's surficial materials are lacustrine and glaciolacustrine sediment (Fig.6). Most of these glacial lakes were small (relative to those in other regions of the Interior Plains) and short lived, rapidly decanting into an adjacent basin once ice retreat established a new lake outlet. Some basins retained lakes long after glacial influences had been removed, and as a result contain lacustrine sediments of nonglacial origin (e.g. David, 1964).

Lake deposits range in thickness from thin veneers (not mapped in Fig. 6) to more than 40 m (Shetsen, 1987). Although they occur most commonly on relatively featureless plains, lake sediments that were deposited on top of stagnant ice now occur in areas of hummocky terrain with up to 10 m local relief (e.g. Klassen, 1991). A suite of facies, ranging from deep-water clays to littoral sands, and deltaic sands and gravels, have been described, although they have generally not been the subject of detailed sedimentological investigations. Glaciolacustrine deposits are commonly laminated, although extensive varved records have not been reported. Clays are generally rich in montmorillonite and hence generally have a low permeability and high plasticity, commonly developing deep desiccation cracks when dried (David, 1964). Lacustrine sands are fine to medium grained, well sorted, and generally less than 5 m thick, in contrast to deltaic sand and gravel deposits that may exceed 30 m in thickness (David, 1964). Outcrops of silt- and sand-dominated lacustrine facies have typically been reworked by eolian processes, producing loess, sand sheets, and dunes (see "Eolian Processes and Landforms").

Eolian deposits

Eolian dunes and loess deposits are extensive in the central Palliser Triangle (Fig. 6). In fact, the Great Sand Hills constitute the largest contiguous occurrence of dunes in southern Canada (David, 1977a). Eolian deposits are particularly sensitive to climatic variability (e.g. Wolfe et al., 1995), and these relationships are discussed in detail in a subsequent section (see "Eolian Processes and Landforms").

Morphologically, all sand dunes in the Palliser Triangle are part of the parabolic dune association (David, 1977a) and are oriented with the prevailing westerly winds. They are derived mainly from glaciofluvial and glaciolacustrine deposits (David, 1964), and dominantly composed of fine (range: very fine to coarse) sand (David, 1977a; Wolfe et al., 1995). Although generally less than 5 m thick, eolian sands may reach 30 m in thickness, not including the height of individual dunes (which may be up to 15 m high; David, 1964). A distinct eastward (downwind) fining often produces blankets of very fine sand and loess to the east of major dune occurrences (Fig. 6; David, 1993).

Loess is widespread across the Palliser Triangle, but tends to be thin and has not commonly been mapped in surficial geological surveys (Vreeken, 1993). The most extensive loess cover occurs on the Cypress Hills (Catto, 1983) and Swift Current Creek Plateau (Christiansen, 1959). Deposits in the Cypress Hills span a wide age range, from Miocene to Holocene, and locally may exceed 6 m in thickness (Vreeken, 1993). Loess on the Swift Current Creek Plateau is very thin, ranging from about 1.4 m adjacent to source sediments (David, 1964) to 0.3 m at the eastern limit of its mapped distribution (Christiansen, 1959). Loess composition is highly variable, reflecting different source materials. Although dominantly silt sized, sand and clay contents as high as 33% and 32%, respectively, have been reported in loess (David, 1964; Vreeken, 1993). Localized occurrences of fine-grained eolian deposits also occur as cliff-top loam (e.g. David, 1972) and leeward-slope deposits (Vreeken, 1993).

Colluvium

On Figure 6, colluvium is only shown mantling the glacially over-steepened north flank of the Cypress Hills/Swift Current Creek Plateau and on heavily dissected pediments of the Wood Mountain Upland. These slope deposits, derived from both Pleistocene sediments (primarily till) and bedrock, may be more than 30 m thick. Clast lithologies are dominated by local quartzites and chert (Klassen, 1991). Although not shown on Figure 6, colluvial deposits are ubiquitous along steep walls of meltwater channels in the Palliser Triangle (see "Valley complex", below). Factors that promote slope failure include oversteepening by glacial or meltwater erosion, the poorly consolidated nature of the bedrock, and the occurrence of swelling clays in bedrock, till, and glaciolacustrine sediments (see "Mass Wasting Processes").

Valley complex

This unit is used to denote complex assemblages of sediment found in most incised river valleys, and cannot be differentiated at the scale of Figure 6. It is mainly composed of alluvium, colluvium, and glaciofluvial deposits, but may also include bedrock and glaciolacustrine sediments. The majority of incised valleys in the Palliser Triangle originated as glacial meltwater channels. As a result, modern streams are commonly highly underfit. Recent alluvium (dominantly silt and sand) occurs as floodplain and terrace deposits adjacent to modern stream courses. Thick deposits (locally >50 m) of colluvium, derived from both bedrock and drift, are ubiquitous along the walls of steeper valleys. For example, Christiansen and Sauer (1988) documented 80 m of fill in the Frenchman River valley (21 m of glaciofluvial deposits, 7 m of landslide debris, and 52 m of undifferentiated alluvium and colluvium). Although such stratigraphic information is rare in the region, similar sequences of varying thickness likely occur in most other meltwater channel systems.

CLIMATE, VEGETATION, AND SOILS

R.E. Vance, S.A. Wolfe, and D.J. Pennock

Present and historical climate

Overview

The continental, subhumid climate of the midlatitude southern Canadian prairies is characterized by low precipitation, very cold winters, and short but warm summers. Between 1961 and 1990, mean annual temperature in the Palliser Triangle was 3.8°C. During the same period, mean January and July temperatures were -13°C and 19°C, respectively (Fig. 7), and mean annual precipitation ranged from about 300 to 450 mm (Fig. 8A; Environment Canada, 1993).

Although useful for describing general characteristics, thirty-year means conceal the high variability which is one of the defining characteristics of the regional climate. This variability is a result of the interaction between Pacific and Arctic air masses that, in turn, is controlled mainly by the region's geographic setting and seasonal variation in the

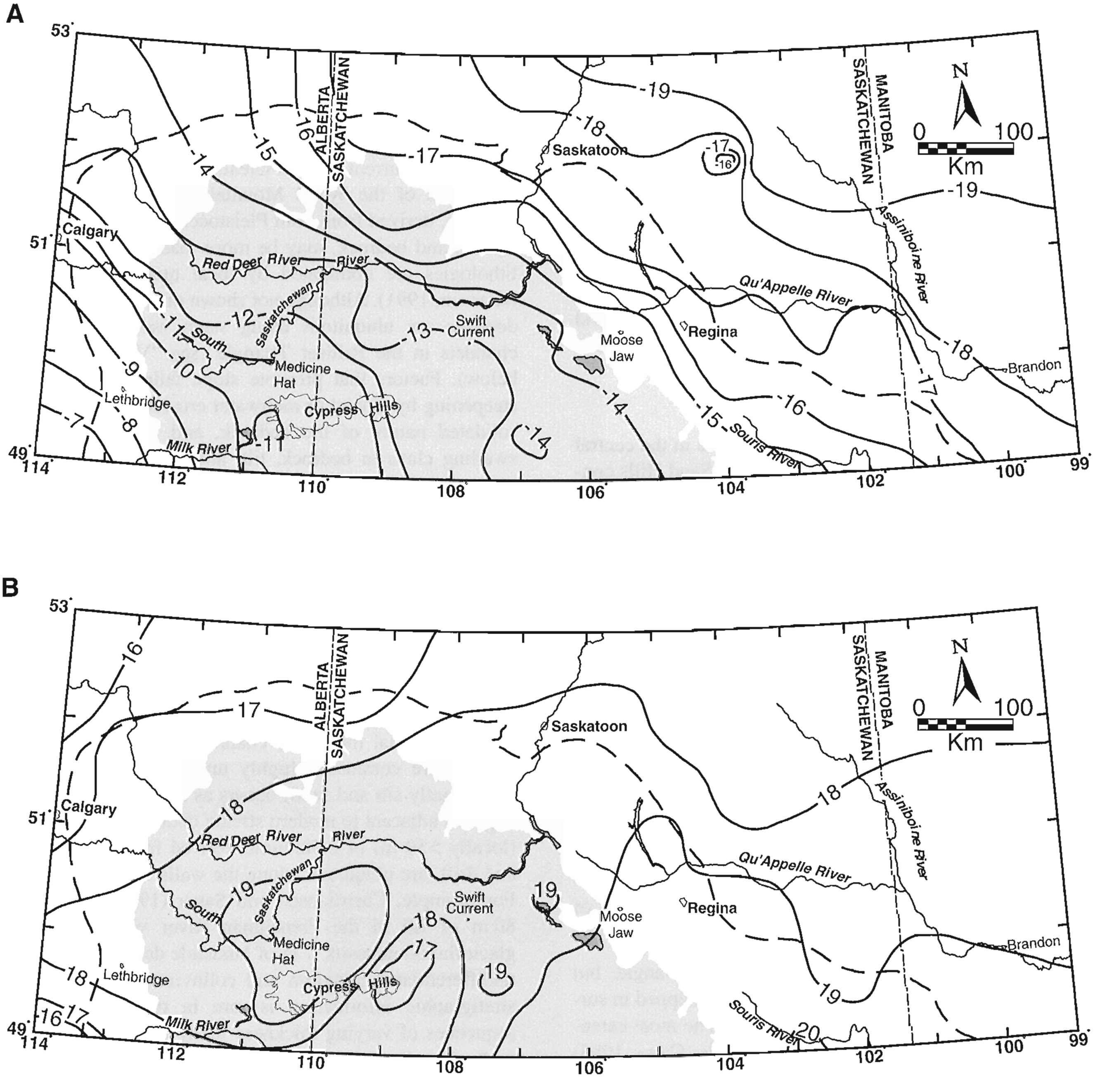


*Figure 7. A) Mean January, and **B)** mean July temperatures in the Palliser Triangle region, 1961-1990 (Environment Canada, 1993).*

latitudinal position of the core of westerly atmospheric flow (the jet stream). The Rocky Mountains to the west form a significant barrier to moist, mild Pacific air (Gullet and Skinner, 1992) which nonetheless prevails over the region for most of summer (although much moisture may be lost on the western slopes of the Cordillera). A southerly shift of the jet stream, coupled with the limited relief of the Interior Plains, promotes incursions of cold, dry Arctic air masses over the Palliser Triangle during winter months. Such dynamics produce the greatest annual temperature range in Canada (Hare and Thomas, 1979). Canadian record highs of 45°C have been reported in southern Saskatchewan (Gullet and Skinner, 1992), while winter temperatures as low as -50°C are not unknown. In addition to these seasonal dynamics, variations in the strength and position of the westerlies can also produce a great range of conditions within any one season.

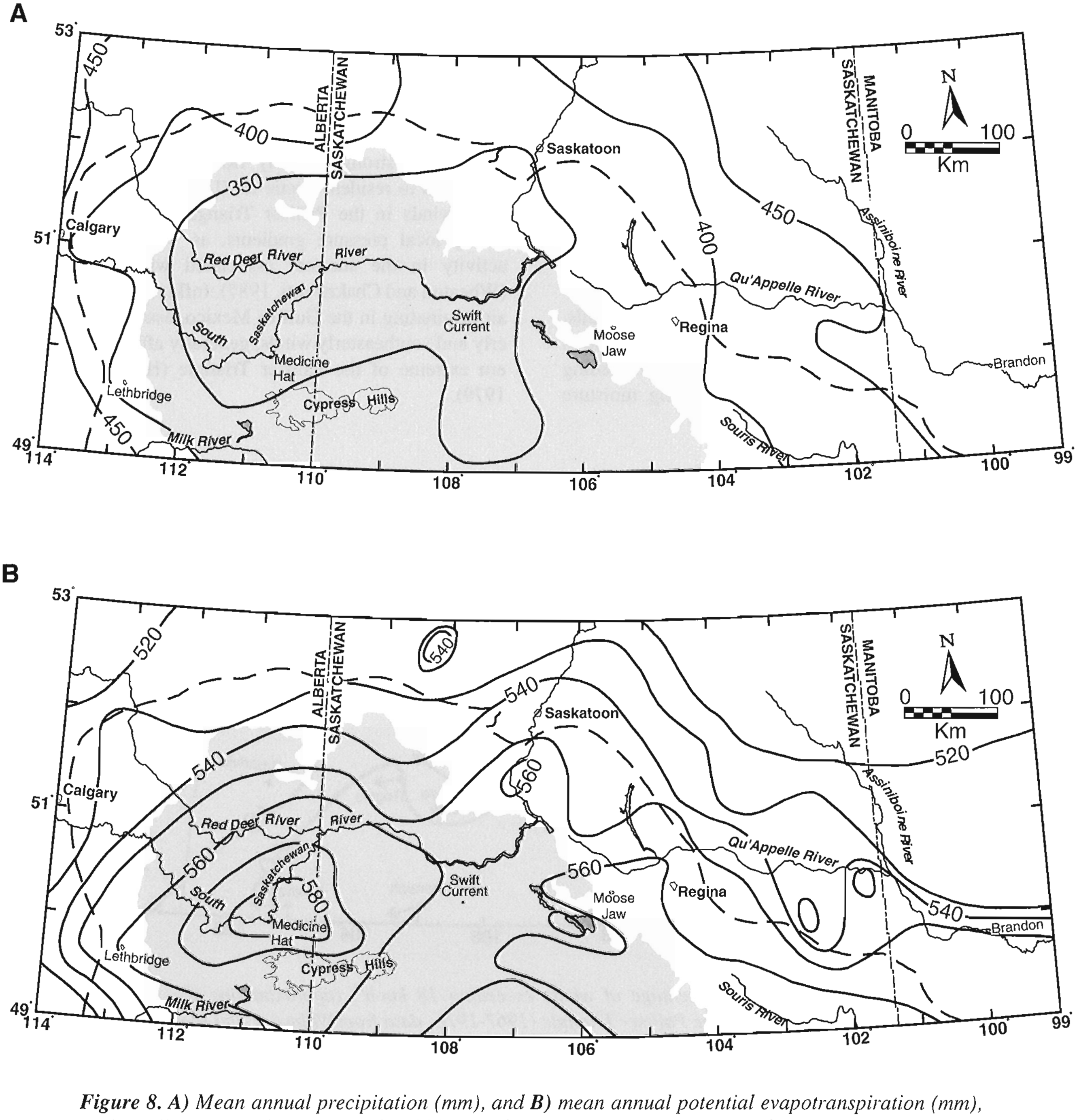


Figure 8. A) Mean annual precipitation (mm), and B) mean annual potential evapotranspiration (mm), in the Palliser Triangle region, 1961-1990; data from Environment Canada (1993). Potential evapotranspiration calculated using the modified Thornthwaite method (Thornthwaite and Mather, 1957).

Most precipitation in the Palliser Triangle falls in spring and early summer. June is typically the wettest month and may account for more than 25% of yearly precipitation (Environment Canada, 1993). Summer rainfall, mainly the product of showers or localized, high-intensity storms of short duration, is variable. Intense rainfall events exceeding 80 mm are not uncommon, and often cause localized flooding (e.g. 160.3 mm of rain fell June 15, 1887 in Regina and 121.9 mm in Medicine Hat on August 14, 1927; Environment Canada, 1993). Low precipitation is typical of most prairie winters, due to the dominance of dry Arctic air masses. Average snowfall between December and February (1961-1990) ranged from about 70 cm (near Kindersley, Saskatchewan; Fig. 2) to 180 cm in the Cypress Hills (Environment Canada, 1993), making up only 30% of total annual precipitation. Orographic influences account for the greater precipitation on the Cypress Hills, compared with the adjacent prairies.

Although summer (defined as the period when mean daily temperatures normally rise above 16°C) is barely three months long, warm temperatures, combined with strong winds and extended daylight, create highly evaporative conditions. With the exception of the Cypress Hills, potential evapotranspiration across the Palliser Triangle is generally greater than 540 mm (Fig. 8B), far exceeding mean annual precipitation, producing a strong moisture deficit. In average years, moisture loss due to evapotranspiration exceeds precipitation by about 30%, whereas in drought years, such as 1987 and 1988, evapotranspiration exceeded precipitation by 60% in the central Palliser Triangle (Wolfe, 1997).

Mean annual windspeeds exceed 20 km·h^{-1} over much of the southern prairies (Walmsley and Morris, 1992), with considerable fetch across the essentially treeless, generally flat to gently rolling terrain. Strong westerly and southwesterly winds prevail throughout the Palliser Triangle (Fig. 9), resulting in significant sediment transport capacity. In the west, winter and early spring chinook winds exceeding 90 km·h^{-1} have been recorded. Although chinook winds are rarely felt east of Alberta (Hare and Thomas, 1979), their influence may extend as far east as south-central Saskatchewan, because Pacific air masses driven over the Rockies by strong westerly flow remain relatively mild compared to resident Arctic air (Longley, 1972). However, most winds in the Palliser Triangle are created through strong local pressure gradients, as well as convectional activity in the summer associated with thunderstorms (Wheaton and Chakravarti, 1987). Influxes of moist tropical air originating in the Gulf of Mexico, associated with easterly and southeasterly winds, generally affect only the eastern extreme of the Palliser Triangle (Hare and Thomas, 1979).

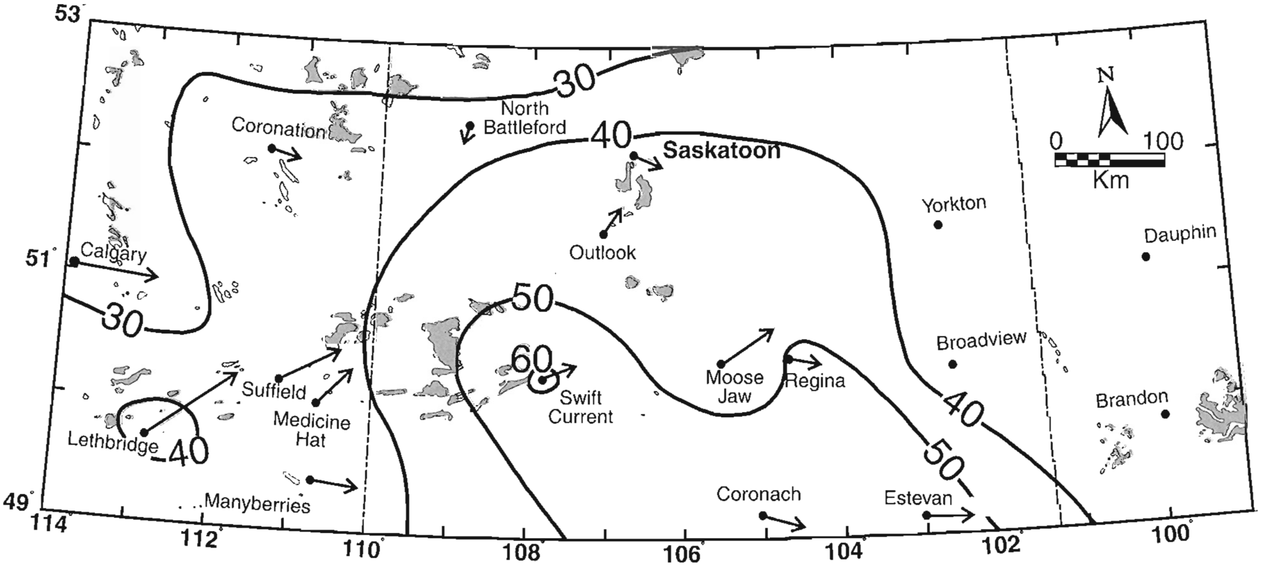


Figure 9. Isolines denoting percentage of winds exceeding 18 km·h^{-1} (approximating the transport threshold for dry sand) across the Palliser Triangle (1967-1976; data from Walmsley and Morris, 1992). Arrows indicate relative magnitude and direction of potential sediment transport (1961-1990; data from Environment Canada National Climate Archive Database). Shaded areas are major dune occurrences (see Fig. 13).

Drought

Because low annual precipitation and high evaporation rates typify the Palliser Triangle, even relatively minor departures from normal precipitation are capable of producing drought. In the twentieth century, widespread drought has occurred within the Palliser Triangle nearly every decade (Chakravarti, 1976). In addition, Captain John Palliser's observations suggest that his survey, carried out between 1857 and 1860, coincided with a drought period no less severe than that of the 1980s (cf. Spry, 1968). However, it is important to note that there is typically considerable variation in drought severity throughout the Palliser Triangle, even during years of greatly reduced precipitation (Chakravarti, 1976).

Droughts of the last 50 years on the southern prairies have been linked to the development of stable, midlatitude high-pressure ridges that displace cyclonic tracks, moist air masses, and fronts to the north (Dey and Chakravarti, 1976; Dey, 1982). Subsidence and temperature inversions associated with these quasi-stationary high-pressure cells produce extended periods with clear skies, high temperatures, and limited convectional storm development. The severe drought of 1988 is a prime example of this synoptic pattern. At that time, the jet stream was displaced north of its normal position throughout most of the spring and early summer and, under a meridional circulation regime (Fig. 10A), a persistent ridge developed over northwestern North America (Trenberth et al., 1988; Namais, 1989). This pattern followed a warm, dry summer, fall, and winter of 1987 (much of southern Alberta and Saskatchewan received less than 50% of the normal precipitation during this period; Wheaton and Arthur, 1989), and little runoff was produced in the spring of 1988. When the critical spring rains failed to materialize, many sloughs and small lakes were dry by June. The ensuing drought was one of the worst this century, rivalling 1937-1938 as the driest on record (Wheaton and Arthur, 1989). June 1988 was the warmest in the instrumented record of the prairies, with mean temperature 4 to 7°C above thirty-year means (Wheaton and Arthur, 1990).

In the absence of upper air data prior to 1950, it is not clear whether blocking high-pressure ridges, similar to those characteristic of 1988, were also a feature of earlier drought events. Of particular interest are the 1920s and 1930s, when recurrent dry spells devastated the agricultural economy of the Palliser Triangle. Isentropic surface data (Namais, 1983), as well as analysis of pressure-pattern movements (Dzerdzeevskii, 1969), suggest that a vigorous zonal circulation pattern (Fig. 10B) prevailed throughout the first half of this century, and was particularly well developed in the 1930s. Such a pattern is a marked contrast to the meridional circulation pattern associated with the 1988 drought. Although details of this drought circulation pattern are poorly known, it nevertheless raises the possibility that earlier Palliser Triangle droughts owe their existence to synoptic patterns significantly different from those that have prevailed in the last 50 years, in turn suggesting that regional expressions of earlier droughts may have been different from those experienced in recent times.

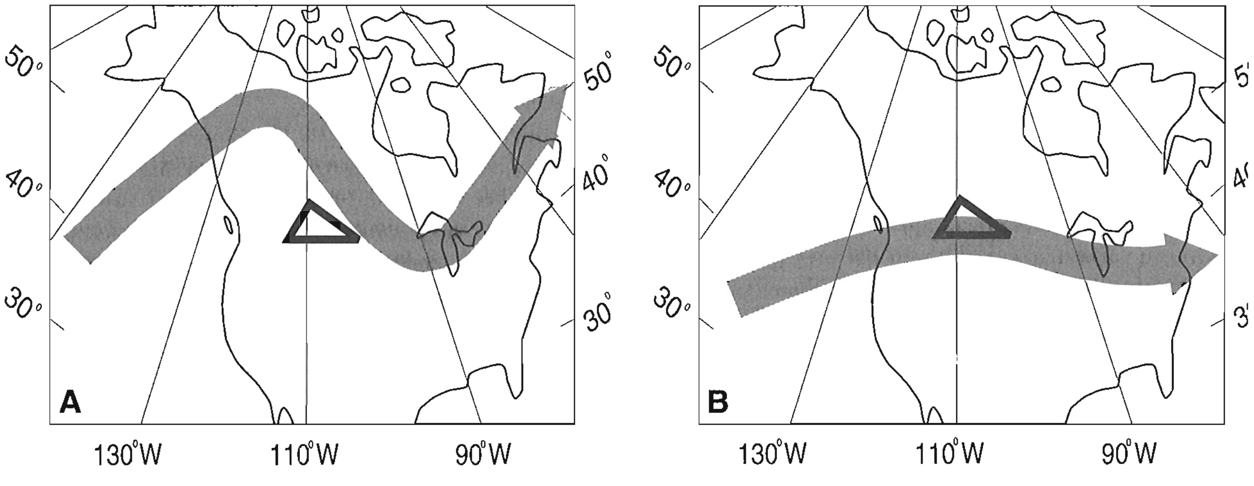


Figure 10. *Synoptic circulation patterns associated with drought on the Canadian prairies; triangle roughly depicts location of the Palliser Triangle.* ***A)*** *Dominant summer 500 hpa circulation pattern from 1961-1967 showing meridional flow with a strong ridge developed over west-central Canada (Dey, 1982). A quasi-stationary high-pressure area over the prairies displaces the jet stream to the north. This synoptic pattern has been associated with recent droughts in the Palliser Triangle, including the severe drought of 1988 (e.g. Namais, 1989).* ***B)*** *zonal flow with minor ridge over the prairies. Dominantly westerly airflow with dry winds descending from mountains onto adjacent plains produces dry conditions across much of central North America. Similar conditions dominated most summers from 1934-1938, as inferred from isentropic charts (Namais, 1983).*

Climate change in the last century

Although dramatic events like the droughts of the 1930s and 1980s have affected both the landscape and the inhabitants of the Palliser Triangle, they may be attributed to short-term excursions from recent normals, representing variability in prairie climate, as opposed to climate change. Underlying these excursions from the mean, however, is a statistically significant warming of 0.9°C in the southern prairie region since the late 1800s, culminating with the 1980s, the warmest decade on record (Fig. 11A; Gullet and Skinner, 1992). Prairie stations also show an increase in the frost-free period and in the number of growing-degree days over the last century; most noticeably in the last 30 years (Bootsma, 1994). Although these trends cannot unequivocally be attributed to global warming, they are consistent with many climate model simulations that suggest increased concentrations of greenhouse gases will result in increased warmth on the northern Great Plains (Karl and Heim, 1991; Karl et al., 1991). Whether a reflection of global warming or not, the trend over the last 100 years in the Palliser Triangle, like global temperature change, has not occurred at a steady rate. Warming between 1890 and 1940 was followed by cooling through to 1970, with resumed warming taking place from the 1970s through the 1990s (Gullet and Skinner, 1992).

Unlike temperature, there is no trend apparent in historical precipitation records for the prairie region (Bootsma, 1994). Rather, precipitation has fluctuated about the thirty-year mean (1961-1990) throughout the last 100 years (Fig. 11B; Environment Canada, 1995). In general, however, wet periods in the early 1900s and 1950s coincided with periods of below-normal temperature, whereas fewer years with above-average precipitation occurred between 1959 and 1990 (generally corresponding to the period of recent warming), than in any previous thirty-year period.

Holocene climate change

Developing a Holocene (last 10 000 years) record of climate change in the Palliser Triangle has lagged behind paleoclimatic research in adjacent regions for a number of reasons, including difficulties in sampling the few suitable wetland study sites and establishing accurate radiocarbon chronologies (Barnosky et al., 1987). However, recent advances in accelerator mass spectrometry (AMS) radiocarbon dating, coupled with the application of new coring techniques and the use of plant macrofossil and lithostratigraphic sequences to chronicle past environmental changes, have produced a new understanding of the long-term dynamics of Holocene climate change in the southern prairie region.

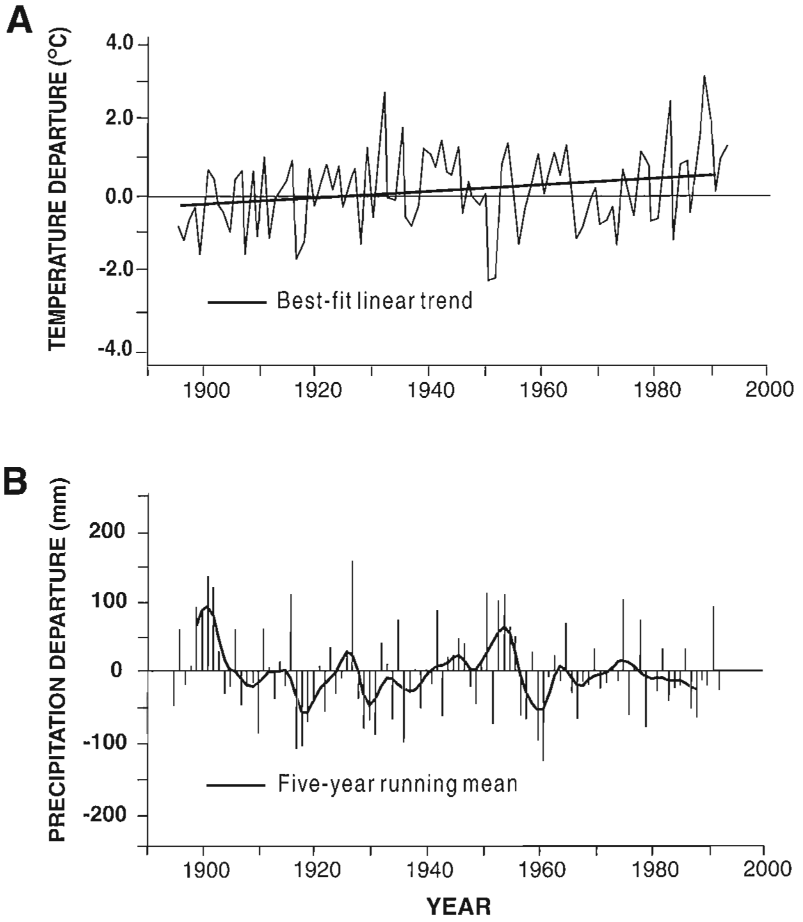


Figure 11.

Instrumental climate records for the prairie region, 1895-1991, expressed as departures from 1951-1980 mean. ***A)*** *temperature (adapted from Gullet and Skinner, 1992); solid line indicates best fit linear trend (significantly different from 0°C at the 95% level).* ***B)*** *precipitation (Environment Canada, 1995); solid line indicates five-year running mean.*

Lithostratigraphic, plant macrofossil, and pollen records from Chappice Lake, a groundwater-fed, shallow, hypersaline lake near Medicine Hat (Fig. 2), reveal that significant changes in lake level and water chemistry have occurred over the last 7300 years in response to climate change (Vance, 1991; Vance et al., 1992, 1993). Pollen and lithostratigraphic sequences from Harris Lake, a small, shallow, hyposaline, groundwater-fed lake that straddles the forest-grassland transition on the northern flank of the Cypress Hills (Fig. 2), provide further insight into Holocene climate change over the past 9300 years (Sauchyn and Sauchyn, 1991; Last and Sauchyn, 1993). Numerous AMS radiocarbon dates on seeds provide strong chronological control at both Chappice and Harris lakes.

The composite paleoclimatic record from these two basins indicates that conditions more arid than at present prevailed through the mid-Holocene (7700-6000 BP), followed by less severe conditions (but still more arid than at present) from 6000 to 4500 BP. At Harris Lake, the effects of increasing effective moisture are registered by ca. 5000 BP, and are followed by the onset of cool and moist conditions typical of recent climate by 3200 BP, with little change to the present. Additional details concerning late Holocene events are recorded in Chappice Lake because it is situated on the prairie floor below the Cypress Hills, an environment sensitive to relatively minor changes in the water balance. Here, declining mid-Holocene aridity (beginning at 4500 BP) was followed by a period of peak effective moisture between 2700 and 1000 BP. A short-lived return to more arid conditions, at about the time of the Medieval Warm Period (ca. 900-1200 AD; Hughes and Diaz, 1994), was followed by a return to generally cool and moist conditions through the Little Ice Age (ca. 1450-1850 AD; Luckman et al., 1993). The historical period (beginning ca. 1880) has been more arid, in general reflecting historically recorded drought events of the 1880s, 1920s, 1930s, and 1980s. Significantly, both the Chappice Lake and Harris Lake records indicate that the dry spells of the historical period pale in comparison to the duration and severity of mid-Holocene droughts.

Other less lengthy paleoecological records from the southern prairies support this reconstruction of a prolonged period of severe mid-Holocene drought. Near-basal AMS radiocarbon dates on sedimentary records from Max, Kenosee, and Antelope lakes (Fig. 2) indicate infilling at all three basins within the last 4000 years, in turn suggesting that they were dry in the mid-Holocene (Vance and Last, 1994; Vance et al., 1995). Paleolimnological investigations of sites north of the Palliser Triangle also indicate that lakes in central Saskatchewan were dry prior to 4000 BP (Last and Slezak, 1986). The water table was also significantly lower than at present throughout the early and mid-Holocene in central Alberta (Schweger and Hickman, 1989), the foothills of southwestern Alberta (MacDonald, 1989) and Montana (Barnosky, 1989), North Dakota (Fritz et al., 1991), and central Manitoba (Teller and Last, 1990). Evidently the mid-Holocene water deficit on the northern Great Plains was severe enough to affect surface waters over a wide area (Vance et al., 1995).

Times of increased effective moisture, compared to the present, are also apparent at some sites, although evidence for these events appears only in records situated in the most climatically sensitive environments. In addition to the Chappice Lake record mentioned above, plant macrofossil and lithostratigraphic evidence from Kenosee Lake also indicates a significant lake-level rise occurred at 2700 BP (Vance and Last, 1994). Devils Lake, North Dakota (Fig. 1), also attained exceptionally high lake levels beginning about 2700 BP (Bluemle, 1991). These records of rising lake levels occur at about the same time that glaciers advanced in the Canadian Rocky Mountains, between ca. 3100 and 2500 BP (Luckman et al., 1993).

Although it is possible to produce quantitative estimates of the magnitude of past climate changes from fossil assemblages, analysis of this type has not yet been applied to Palliser Triangle records. However, transfer functions have been used to convert two pollen records from central Alberta (Lofty Lake, Fig. 1; Vance, 1986) and southwestern Manitoba (Riding Mountain Uplands, Fig. 2; Ritchie, 1983) into estimates of Holocene temperature and precipitation dynamics. Because of the relative proximity of these sites to the Palliser Triangle, the results provide a reasonable starting point to assess the magnitude of Holocene climate changes experienced in the southern prairies. Both records suggest a similar history of temperature changes, with growing-season temperature rising rapidly ca. 10 000 BP and remaining above present values throughout much of the Holocene. However, both the magnitude and timing of peak temperatures vary considerably between these two sites. Taking into account the limitations of both the records and the analytical techniques, a reasonable estimate of the increase in growing-season temperature from the two records would be approximately 1.5 to 3°C between 9000 and 3000 BP (Vance et al., 1995). An estimated growing-season precipitation deficit of 50 mm at Lofty Lake between 8000 and 6000 BP suggests that aridity registered at both Chappice and Harris lakes was the result of long-standing above-normal temperatures coupled with a Holocene low in growing-season precipitation. Zoltai and Vitt (1990) produced comparable estimates based on changes in the distribution of peatlands in the Canadian western interior, suggesting mean July temperature was about 0.5°C warmer than today and mean annual precipitation was 65 mm lower than at present, prior to 6000 BP.

Vegetation

The Palliser Triangle occupies the northern reaches of the North American Great Plains; an expansive interior grassland that lies in the rain shadow of the Rocky Mountains. A paucity of available moisture limits tree and shrub growth to lake and stream margins, north-facing slopes of coulees, and uplands like the Cypress Hills. As a result, a northern variant of mixed prairie grassland is the native vegetation on gently rolling terrain throughout much of the Chernozemic Brown and Dark Brown soil zones of the Palliser Triangle.

This native vegetation cover, commonly referred to as the 'northern mixed-grass prairie' (Risser et al., 1981) or simply 'mixed prairie' (Coupland, 1950, 1961), spread throughout the Canadian portions of the northern Great Plains in the early Holocene, ca. 10 000 years ago (Ritchie, 1976). It is bounded to the north and west, where the moisture deficit is not as great, by Fescue prairie, the characteristic cover of drier portions of the Black soil zone (Moss, 1944; Coupland, 1961).

Although the evolutionary history of elements of the mixed prairie may be traced to the Oligocene, over 25 million years ago (Risser et al., 1981), little is known about the history of its major constituents, or factors that shaped the ecozone's development. However, it is fair to say that the introduction of cattle and European agricultural practices, coinciding with a sharp reduction in fire frequency and the elimination of large buffalo herds in the late 1800s, were likely as significant as any preceding events in the history of the mixed prairie. In the 150 years since the onset of these changes, most mixed-grass prairie vegetation has either been supplanted by cereal crops or modified by grazing and the introduction of non-native species. A lack of comprehensive surveys prior to the arrival of European settlers means it is impossible to quantitatively assess the nature and extent of these impacts on the Palliser Triangle vegetation. The first extensive vegetation surveys were conducted in the 1940s by Coupland (1950) and, although he later recognized the lingering effects of the 1930s drought on the northern mixed-grass prairie, he maintained that of all the changes wrought by European settlement, the elimination of fire was probably the single most significant event (Coupland, 1961). Coupland's surveys (1950, 1961) show that although considerable compositional variability is inherent to the northern mixed-grass prairie (due mainly to the impacts of relief and aspect on moisture availability), most associations are dominated by spear grass (*Stipa comata*), porcupine grass (*Stipa spartea*), June grass (*Koeleria marcantha*), western wheatgrass (*Agropyron smithii*), northern wheatgrass (*Agropyron dasystachum*), plains muhly (*Muhlenbergia cuspidata*), and blue grama (*Bouteloua gracilis*). Although numerous other species form important subdominants or less abundant members in a variety of mixed prairie assemblages, it is the variation of these seven major species that Coupland used to define all northern mixed-grass communities.

Although moisture variations affect community composition, the mixed prairie grassland is well adapted for surviving in a region that suffers from periodic moisture shortages. In addition to adjustments in community composition, the yearly growth cycle is interwoven with seasonal moisture variations. Although almost 95% of the species are perennial, some with life spans greater than 20 years, many are cool-season forms that begin growth in early spring, flower by June, and are dormant by July (Risser et al., 1981). Although renewed growth may occur by vegetative propagation in the fall, most growth is completed by the time summer heat places great stress on prairie water reserves and prairie fires are most likely to occur. Thus, most native species are dormant when disturbances are most likely to occur. However, a series of drought years will not only promote widespread development of northern mixed-grass prairie assemblages characteristic of drier sites, but also will reduce overall cover, as it did in the 1930s (Coupland, 1958, 1959; Tomanek, 1959). In this setting, the effects of fire and grazing are potentially more serious. Although some information is available on the effects of decade-long drought events like the 1930s (Coupland, 1958, 1959), very little is known about the impacts that more severe and prolonged drought intervals exert on vegetation, such as those that prevailed through the mid-Holocene. This gap in understanding is mainly due to the insensitivity of pollen records in grassland environments, since most of the major mixed prairie species cannot be distinguished on the basis of pollen alone (Barnosky et al., 1987; Vance and Mathewes, 1994). This limitation prohibits detailed reconstruction of native vegetation responses to extended drought.

On uplands like the Cypress Hills, orographic influences create conditions more conducive to the establishment of woody vegetation. Here, north-facing slopes, seepage areas, and stream banks support populations of trembling aspen (*Populus tremuloides*) balsam poplar (*Populus balsamifera*), lodgepole pine (*Pinus contorta*), and white spruce (*Picea glauca*), which extend downslope in protected areas onto the prairie floor. Fescue prairie dominates drier sites on the upland (Looman and Best, 1979). Pollen analysis of sediments from Harris Lake, a small basin situated near the current grassland-forest ecotone on the north flank of the Cypress Hills, shows that this ecotone moved upslope in response to warm and dry climatic conditions during the mid-Holocene, ca. 7700-5000 BP (Sauchyn and Sauchyn, 1991). Other uplands in southern Saskatchewan, such as Wood Mountain and Moose Mountain, also support a similar type of forest cover, although spruce is not as common as it is on the Cypress Hills. Forest cover on the Moose Mountain upland is also distinguished by an extensive paper birch (*Betula papyrifera*) population. Woody vegetation is also found in the Palliser Triangle in coulees (Coxson and Looney, 1986), interdune areas (see "Eolian Processes and Landforms") and in deeply incised river valleys, where groves of cottonwood (*Populus acuminata, Populus angustifolia*, and *Populus deltoides*) colonize alluvial flats.

Soils

The major soils present the Palliser Triangle strongly reflect the subhumid climate and grassland vegetation which dominate the area (Anderson, 1987). The soil orders result from differences in the type and intensity of soil-forming processes; these differences are, in turn, largely due to differences in surficial sediments (soil parent materials) and the stability of the surfaces during the Holocene.

The region is dominated by soils of the Chernozemic Order (Fig. 12, back pocket). The Chernozemic A horizon has high levels of organic matter in the upper 10 to 50 cm of the soils due to above-ground and rooting-zone inputs of biomass from the original grassland communities. The high organic-matter inputs are accompanied by minimal weathering of the B horizon to form a Bm horizon, and the deposition of calcium carbonate at the base of the B horizon to form a Cca horizon. The different variants of the Chernozemic Order present within the region, which are represented as Great Groups in the Canadian System of Soil Classification (Agriculture Canada Expert Committee on Soil Survey, 1987), differ in terms of the amount of organic matter present, as reflected in the colour of the A horizon. Chernozemic Brown (BC units of Fig. 12) soils cover the largest area in the region. These soils have organic-matter contents of about 3% loamy to clay-loam parent materials and as little as 1 to 2% sandy variants (Rostad et al., 1993). The higher elevations of the Cypress Hills Plateau and the Swift Current Plateau are occupied by Chernozemic Dark Brown (DBC units) soils with organic-matter contents of 4%; the highest portions of the Cypress Hills have Chernozemic Black (BLC units) soils with organic-matter contents of 4 to 5% (Rostad et al., 1993).

Several large areas of Solonetzic soils also occur throughout the Palliser Triangle (BS units). The diagnostic horizon of soils of the Solonetzic order is the Bnt horizon (or hardpan layer) which is characterized by high sodium contents relative to other exchangeable bases. High sodium contents initially facilitate the translocation of clay from the A horizon to the B horizon, leading to the formation of the clay-rich Bnt horizon. The Bnt horizon commonly overlies a salt-rich C horizon (Csa or Cksa horizon). Solonetzic soils reflect a local or regional concentration of sodium in the soil profile. The concentration of sodium can occur due to either high initial levels in the source glacial sediments (the lithogenic model of Pawluk, 1982), or from past or current discharge of sodium-rich groundwater (paleohydrological and hydrological models of Pawluk, 1982). Solonetzic soils which arise from the latter two sources are closely related to areas of saline soils.

The final soil order of regional significance is the Regosolic Order. Regosolic soils reflect the lack of sufficient surface stability for pedogenesis and horizonation to occur. Regosolic soils are characterized by the lack of a B horizon, and, in extreme cases, the lack of an A horizon as well. They are associated with three distinct environments: unstable sandy soils on the sand hills of Alberta and Saskatchewan (R-s units), valley slopes of the major river systems in the area, and with the areas of exposed Tertiary bedrock in the Frenchman River valley and the Wood Mountain area of Saskatchewan. The latter two areas exhibit a wide range of soil textures and are mapped as R-var units on Figure 12.

EOLIAN PROCESSES AND LANDFORMS

P.P. David

Introduction

Eolian deposits and associated features are widespread in the Palliser Triangle, where sand dunes alone cover more than 3400 km^2 (Fig. 13; David, 1977a). Wind-blown sediments of varying grain sizes produce characteristic landforms including sand dunes, silty to fine-grained sand sheets and loess, and loamy sediments forming cliff-top deposits (David, 1970, 1972; Vreeken, 1993). Tephras are also wind-transported sediments, commonly found embedded within other deposits (David, 1970; Westgate et al., 1970; Westgate 1975; Vreeken and Westgate, 1992). Finally, erosional features, including wind-faceted glacial erratics, steep valley slopes exposed to storm winds (David, 1972, 1995a), and so-called wind-aligned coulees (Beaty, 1975), also form part of the eolian landscape in the southern prairies.

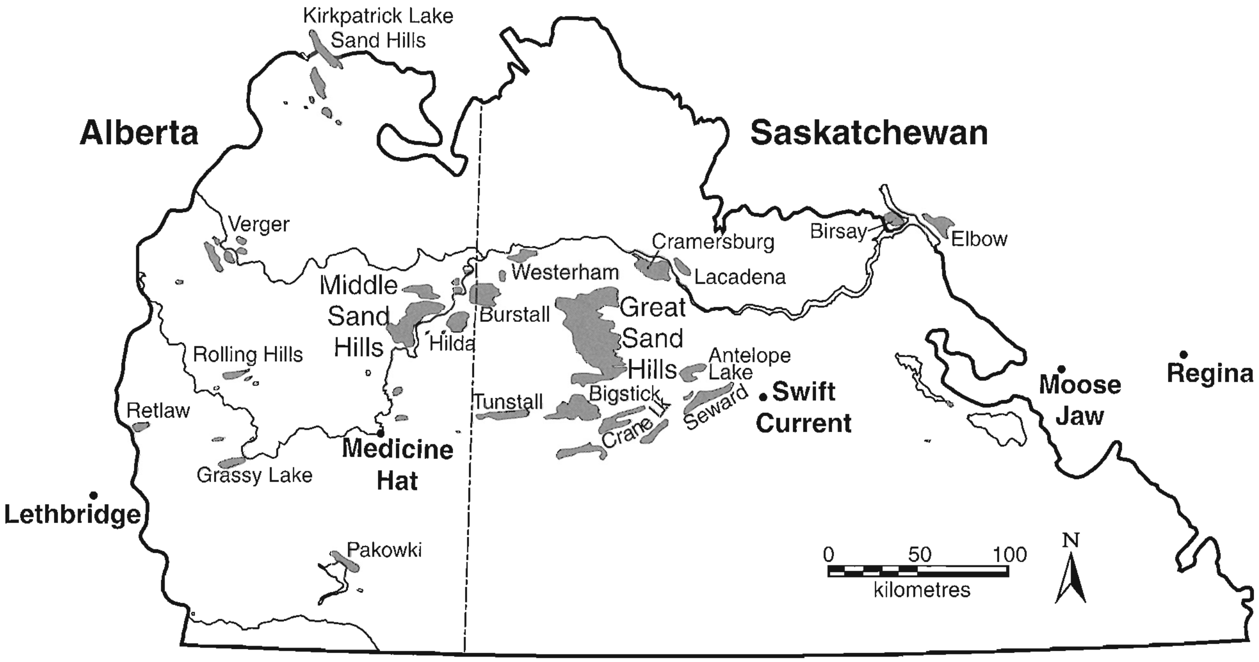
Widespread eolian activity in the Palliser Triangle during the 1920s and 1930s, in part promoted by cultivation of marginal land, raised concerns about hazards such as dust storms and soil degradation associated with wind erosion, and prompted studies on soil drifting (Chepil, 1945, 1957), dune occurrences (Johnston and Wickenden, 1935), and surficial water resources (Main, 1935). Similar types of studies continue at present, geared mainly toward production of wind erosion risk maps and models (e.g. Coote and Pettapiece, 1987; Coote and Padbury, 1988a).

In addition to being potential geological hazards, eolian phenomena provide important proxy evidence of both past and ongoing global change that can be used to predict climatic impacts (e.g. Vance and Wolfe, 1996). The following discussion, based on research from within the region and an understanding of eolian processes developed in other areas, provides an overview of the eolian environment in the Palliser Triangle. A brief description of the types and occurrences of erosional forms and fine-grained eolian deposits is followed by a more detailed discussion on the origin, morphology, and climatic significance of sand dunes.

The eolian system

The eolian landscape is a palimpsest of forms and features that can be interpreted through detailed study of modern morphological and structural elements. Moreover, evaluation of the causative factors of dune formation improves understanding of the interactions between driving forces (energy and material input) and the processes generated by them. Wind erosional features and eolian sediments are the most obvious elements of the eolian system within the Palliser Triangle, but only constitute one component of the entire system. Dependent and independent variables influencing the eolian system may include climatic, geological, morphological, hydrogeological, pedological, botanical, zoological, and anthropogenic factors (David, 1977b, 1981a). All of these factors are both time and space dependent.

Field observations in the Palliser Triangle show that short-term climatic fluctuations do affect eolian phenomena (e.g. Wolfe et al., 1995), with response times dependent on the nature and extent of the climatic fluctuations, the size of the affected object, and the magnitude of the resultant morphological change (cf. Wright, 1984; Sweet, 1992). Morphological modifications to eolian features that are caused by climate provide evidence that may be used to both interpret past climatic change and to assess future climatic impacts.



ALBERTA

Name	Area (km^2)
Retlaw	39
Pakowki Lake	49
Grassy Lake	62
Hilda	62
North of Medicine Hat	67
Verger	111
Rolling Hills	115
Kirkpatrick Lake Sand Hills	198
Middle Sand Hills	418

SASKATCHEWAN

Name	Area (km^2)
Lacadena	23
Westerham	39
Tunstall	60
Antelope Lake	70
Seward	109
Elbow	140
Birsay	142
Burstall	142
Cramersburg	163
Bigstick - Crane Lake	362
Great Sand Hills	1069

Figure 13. *Principal sand dune occurrences (shaded) in the Palliser Triangle. Names and areas from David (1977a).*

Wind erosion

Wind erosion is widespread within the Palliser Triangle, as there are few natural obstructions to wind flow (see "Climate, Vegetation, and Soils"). Even though vegetation forms an efficient barrier to wind abrasion, most slopes and elevated surfaces were periodically exposed to wind erosion as a result of prairie fires, a common occurrence prior to the arrival of European settlers. The efficacy of fire in triggering wind erosion is related to antecedent moisture conditions. Under most circumstances the impact may be minimal if there is sufficient ground moisture to allow vegetation to reestablish quickly (Seppälä, 1981; Filion, 1984). For example, grassfires in the Great Sand Hills (Fig. 13) in the late summer of 1967 (David, 1969) did not initiate large-scale wind erosion, mainly because they occurred at a time when available moisture was relatively abundant. However, under conditions of prolonged drought, when the protective vegetation cover is in decline due to moisture stress and the surface becomes increasingly prone to wind erosion, fire can be an effective mechanism promoting wind erosion by denuding the vegetation cover at a time when recolonization rates are reduced.

The coulees of the southwestern Palliser Triangle have been cited as examples of large-scale wind erosion (Beaty, 1975; Vreeken, 1993), as they are orientated parallel to the prevailing winds. Although some researchers have questioned the causal role of wind in producing these 'wind-aligned coulees', the idea has not been rejected by others (e.g. Rahn, 1976). Indeed, wind must play some role in aligning gullies (Stokes, 1964a), just as it does with exposed scarps (Shawe, 1963). However, the exact mechanisms responsible for coulee alignment remain poorly documented. While wind can effectively erode unvegetated slopes, this alone is not capable of creating coulee alignment patterns observed in the Palliser Triangle. More likely, it is the combined effect of slope deflation and preferential cliff-top deposition forming ridges above spurs, resulting in aligned overland flow on the prairie surface (cf. Rahn, 1976), that promotes the extension of coulees parallel to one another and to wind direction, an alignment that appears unrelated to underlying structural control (see "Mass Wasting Processes").

Small-scale eolian erosional features are not commonly described within the Palliser Triangle. This may, in part, represent an oversight, but also reflects the absence of resistant bedrock outcrops in areas of potential sandblast, as ventifacts are most common where wind transports both fine- and coarse-grained sediment (cf. Dylik, 1951; Whitney, 1979; David, 1981b). Nevertheless, wind-faceted and wind-polished rocks have been observed in several dune areas where eolian deposits are thin and glacial erratics have been exposed.

Loess

Loess is formed by suspension settling of fine-grained, wind-transported particles. It is the product of long-distance transport (e.g. Swineford and Frye, 1945), in contrast to sand that is transported primarily through saltation over short distances, forming dunes. The dominant grain size in loess is silt, although coarser particles may occur as individual layers within proximal loess deposits (Krinitzsky and Turnbull, 1967; Olson and Ruhe, 1979) or as extensive deposits adjacent to source areas (David, 1964; Mycielska-Dowgiallo, 1965). Regional changes in grain size and other physical properties of loess may aid in determining source areas (Simonson and Hutter, 1954; Lugn, 1962; Ruhe and Olson, 1980; Ruhe 1983). In the Palliser Triangle, sources are dominantly glacial, fluvial, and to a lesser degree, lacustrine deposits. For large-scale deflation to occur over such deposits, the region must be largely free of vegetation (cf. Bryan, 1945).

Although early soil surveys of the prairie provinces provided a great deal of information on the regional distribution of dune areas, little attention was paid to loess, despite the fact that it is an important surficial deposit (cf. Mitchell et al., 1944). Thorp and Smith (1952) show relatively large areas of the Palliser Triangle mantled by variable thicknesses of loess, which fairly well approximates the more important areas of loess accumulation. However, the true extent of the loess cover is generally much greater than is shown on the most detailed soil maps. Although the regional distribution of loess deposits has been addressed in several studies (Christiansen, 1959; David, 1964, 1971; Souster et al., 1977; Catto, 1983; Vreeken 1986, 1993; Vreeken et al., 1989), it is noteworthy that none approach the extent of similar deposits in the United States (Russell, 1944; Thorp and Smith, 1952; Krinitzsky and Turnbull, 1967).

The age of loess in the Palliser Triangle ranges from Miocene (Vreeken, 1993) to Holocene. Deposition was most extensive during Late Pleistocene deglaciation, although deflation in semiarid areas has resulted in periodic localized deposition of loess throughout the Holocene. The influence of climate on the localized deposition of Holocene loess has not been investigated.

Eolian cliff-top loam

Wind-blown sediments overlying steep slopes are referred to as eolian cliff-top deposits (David, 1972; cf. Stokes, 1964b). In the Palliser Triangle such deposits, sometimes more than 6 m thick, have a poorly sorted loamy composition containing large particles and pebbles that could not have been transported in suspension, thereby distinguishing them from loess (Fig. 14; David, 1972). Cliff-top deposits have been recognized at many localities within and outside the Palliser Triangle (e.g. Vreeken, 1989, 1993). The sediments were presumably transported by storm winds (see "Climate, Vegetation, and Soils") almost vertically up steep slopes, with coarse-grained material deposited just above the cliff as wind speeds diminished, and the finer fraction transported a few tens or hundreds of metres beyond. Incipient Ah soil horizons within cliff-top deposits record intervals of minimal accumulation. Deposition is dependent upon the availability of colluvium, which is able to accumulate on the slopes during dry intervals but is removed by slopewash when spring rains are abundant (David, 1995a). Cliff-top deposition still occurs today.

Tephras

Wind-transported volcanic ash has been recorded within other fine-grained eolian deposits in many parts of the Palliser Triangle (Christiansen, 1961; David, 1970; Westgate et al., 1970, 1977; Westgate, 1975; Vreeken and Westgate, 1992; Vreeken, 1993). Because tephras can be identified with relative ease and are rapidly dispersed by wind, they are excellent stratigraphic markers. Recent advances in absolute dating techniques, allowing very small samples to be dated with precision (e.g. Clague et al., 1995), have greatly increased the value of these sediments as chronological tools.

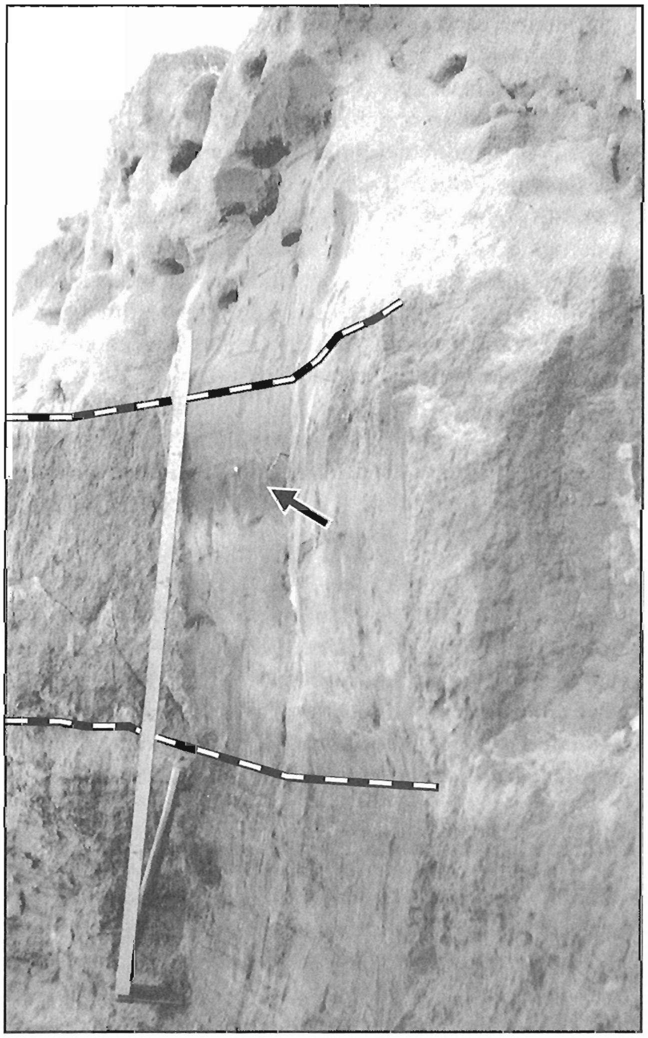


Figure 14. *River bluff exposing fine-grained eolian sediments. Basal unit is stratified fluvial sand overlain by loess with a buried soil near its top (arrow), capped by cliff-top loam. Measuring stick is about 1.5 m. Photo courtesy of P.P. David.*

Paleosols

Paleosols, former soil horizons that developed on the land surface and were subsequently buried by renewed sedimentation, are not uncommon features in eolian deposits (Fig. 15). In addition to their importance as stratigraphic markers, pedomorphological attributes provide important paleoenvironmental information (e.g. Hogan and Beatty, 1963; Ruhe, 1968; Begét, 1990; Vreeken, 1993). Furthermore, paleosols often contain the only significant concentrations of organic carbon in eolian deposits, making them invaluable sources of material for radiocarbon dating (e.g. David, 1970, 1971, 1972, 1993, 1995a).

Sand dunes

To understand the climatic constraints on sand dunes within the Palliser Triangle, a review of dune classification and the climatic significance of the various morphological features is required. Perhaps the single most important observation is that all sand dunes in the region are of the parabolic type, an assemblage that includes a variety of associated features besides the basic parabola form (David, 1977a; Table 1). It

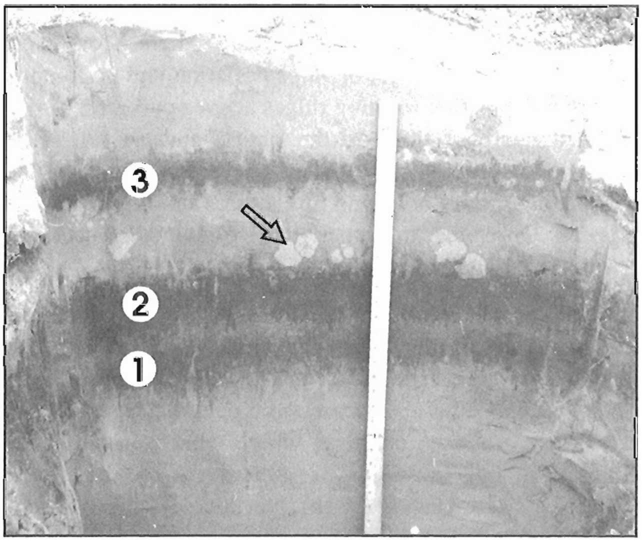


Figure 15. *Section in stabilized parabolic dune exposing three buried Ah soil horizons (numbered). The light, irregular patches (open arrow) are infilled burrows. Photo courtesy of P.P. David.*

is also important to note that dune types characteristic of desert regions are conspicuously absent from the Palliser Triangle (David, 1979).

A classification based on dune morphology should not only provide information on the dunes themselves but also identify characteristics of the environment where they were formed (cf. McKee, 1979). In many dune classification schemes (e.g. Aufrère, 1933; Melton, 1940; Smith, 1953; David, 1977a; McKee, 1979; Mainguet, 1984), parabolic dunes and blowout features are grouped with other dune features, implying that they all belong to the same hierarchical division. Such groupings ignore the obvious first-order environmental subdivision of sand dunes, namely parabolic dunes as opposed to all desert types (David, 1979).

The presence or absence of vegetation on and around dunes has been commonly used for first-order dune grouping, incorrectly suggesting a causal relationship between vegetation and dune morphology (cf. Fryberger et al., 1984). This simple criterion disregards the key role of climate. Parabolic dunes are absent or rare in deserts (i.e. arid to hyperarid environments), but are widespread in more temperate (semiarid to humid) regions. Conversely, active dunes with morphologies characteristic of desert regions (e.g. barchan dunes) are generally absent in semiarid to humid regions. These basic observations suggest that both sand mobility and vegetation are controlled by the available moisture in active dunes, but do not imply a causal relationship between vegetation and dune morphology. The moisture parameter separates dunes into two distinct categories: 'dry-sand' and 'wet-sand' (David, 1979). All parabolic dunes, and therefore all dunes within the Palliser Triangle, are 'wet-sand' dunes. Today most dune areas are stable, containing only a few active dunes.

Morphological elements of parabolic dunes

Parabolic dunes have a slipface that is convex in plan view and wings that, when clearly developed, point upwind. Their principal morphological elements consist of a head, slipface, back slope, wings, back ridge, and blowout depression (Fig. 16; David, 1977a). Other features include summital points, an axial low, and back scarps. Not all elements are present in all dunes, and it is important to recognize that only when dunes are rapidly stabilized will the morphological features of stabilized dunes be the same as those of active parabolic dunes (Fig. 17; David, 1972, 1981b, 1988).

The bulk of the sand forms the dune head, and downwind migration results from deposition on the slipface. The gently inclined back slope is the site of sand influx, through-flow, and loss. The wings and head form an aerodynamic unit that is the transport surface of the dune. Typically, one wing is wider and longer than the other, because occasional cross-winds tend to preferentially build up one side of the dune. Inside the wings and head is the blowout depression, a zone of net erosion. The two wings may be joined at their upwind ends by the back ridge (Fig. 18). This arcuate feature is concave downwind in plan view, and irregular in height and width (David, 1979, 1988). It is produced by multidirectional winds depositing sand removed from the blowout depression. Back ridges are absent from parabolic dunes that developed under a unidirectional wind regime (David, 1981b, 1988).

In addition to these basic morphological elements are dune-track ridges, relatively rare features that mark the former position and shape of the back base line of the dune head (Fig. 18; Table 1). These arcuate ridges, sometimes slightly sinuous or irregular, always occur in groups connecting the two wings across the blowout depression. First described in desert regions (Kerr and Nigra, 1952), dune-track ridges in the Palliser Triangle form when the bases of dunes are stabilized by vegetation. This typically occurs during periods of peak groundwater levels, that may even flood interdune areas (David, 1964, 1977a, 1981a, 1993). Dunes in the Palliser Triangle seldom have more than five or six dune-track ridges, although as many as 30 such ridges are found elsewhere in Canada (David, 1981a).

Parabolic dune association

The term 'parabolic dune association' (David, 1977a) refers to a grouping of dunes and related features commonly found within wet-sand dune occurrences, including the Palliser Triangle (bold terms in the following paragraphs are found in Table 1). The primary feature of the parabolic dune association is the **parabolic dune**. Parabolic dunes originate in two ways: either from the transformation of dry-sand transverse dunes (due to increasing humidity) to **open** parabolic dunes, often with a large radius of curvature; or through the formation of new blowouts (including reactivation of stabilized dunes), commonly producing **closed** parabolic dunes with back ridges. A second useful morphological classification, directly related to sand availability, describes the area between the wings of the dune which may become occupied by the dune head as it increases in size. This area between the wings may be either **unfilled**, signifying limited sand supply and a resulting narrow head, or it may be **partially filled** or **filled**, indicating increasing sand supply with progressively larger heads (Fig. 17, 19). Where parabolic dunes develop in areas of limited sediment supply under the influence of strong unidirectional winds, **elongate** dunes will result (David, 1981b, 1988). The descriptors **symmetric** and **asymmetric** refer to wing development, with asymmetric dunes, fairly common in the Palliser Triangle, reflecting the action of cross-winds. It should be noted that parabolic dunes can occur in composite arrangements (twinned, in-line, en échelon, in-succession, superimposed, and divergent; not

Table 1. Eolian sand dunes and associated features of the Palliser Triangle.

Feature[1]	Modifier or subtype	Morphology	Occurrence	Origin	Sediment supply	Vegetation cover	Water table	Climatic significance
Parabolic dunes	general descriptor	parabolic shape with slipface convex downwind, wings pointing upwind	often in large groups, axes aligned parallel to dune-forming wind	indicative of moist sand, breakdown of transverse dunes, or from blowouts	low - high	low	deep	semiarid / subhumid conditions
	open	wings not connected at upwind end	areas of limited sand supply	as above	low - moderate	absent - very low	deep - average	as above
	closed	wings joined by a semi-circular ridge at their upwind ends (see back ridge)	either on reactivated or new blowout dunes	deflation of sand marking upwind limit of dune	moderate - high	moderate - high	average - shallow	formerly humid
	partially filled or filled	area between wings may be partially or fully filled with sand extending the head upwind	areas of increasing sand supply	uninterrupted supply of sand to the head of the dune	high - unlimited	low	deep	drought
	elongate	wings extended upwind, generally keeping asymmetric profile and gently inclined crest line	in groups above coarse-grained source deposits	rapid migration due to limited supply or strong winds	low	low - moderate	deep - average	strong uni-directional wind
	symmetric, asymmetric	equally well (symmetric) or unequally (asymmetric) developed wings	generally in groups	asymmetry due to side winds prior to stabilization	moderate	low - moderate	average- shallow	cross-winds
Ridge-sided (low-front) dune		high ridge-like wings, low head; one good or several low slipfaces	where high vegetation is absent in front of stabilized dunes	remobilization of head of partially or completely stabilized dune	low - moderate	high on wings	deep - average	drought conditions
Shield dune		semicircular in plan view with straight slipface oblique to general direction of dune migration	often in groups associated with other parabolic dunes	original parabolic dune reoriented by oblique cross-winds	moderate - high	low - moderate	deep	changed wind direction
Blowout features	windpit or dune crevasse	oval to elongate steep-sided depression, commonly widens downwind	top or side of stabilized dunes and sand ridges	breaching of vegetation cover and deflation by wind	high	high	deep	drought conditions
	blowout hollow	circular to slightly elongate oval, shallow depression of limited size	at edge of dune fields on thin source deposits	breaching of vegetation cover and deflation on thin sheet	low	moderate - high	deep - average	drought conditions
	blowout depression	circular to elongate, variable depth, floored by nonsandy deposits	upwind of dunes and blowout ridges	removal of sand by deflation to form constructive features	very low - high	low - high	deep - shallow	extended drought
	deflation area	sizable area free of depositional eolian features, limited by border ridges and dunes at downwind edge	back of dune blankets or upwind edge of dune area	almost complete deflation of sand, often exposing nonsandy material	moderate - high	moderate - high	deep - average	extended drought
	blowout ridge	low, concave upwind, arcuate ridge with gentle slopes and rare slipface	downwind edge of blowout hollow	deposition of sand eroded from blowout depression	low	low	average - shallow	drought
	blowout dune	parabolic, attached to blowout depression, multiple slipfaces produce chaotic surface configuration	stabilized dune areas and where dune activity is sporadic	deflated sand deposited on lee side of blowout depression	moderate - high	moderate	deep - average	drought

Dune ridges	back ridge	arcuate ridge, concave downwind, irregular in plan view, irregular crest-line	upwind end of closed parabolic dune; defines upwind limit since last stabilization of dune	sand accretion at upwind edge of blowout depression and/or outer ridge left behind by reactivation of stabilized dune	moderate	high	average	close of long-term moist conditions
	dune-track ridges	arcuate or slightly irregular ridges in plann, regular crest-line; connect wings across blowout depression	in low-lying areas periodically flooded by high groundwater table	moisture-promoted vegetation stabilizes sand at base of dune	moderate	high	shallow - cyclic rises	short-term moist conditions
Sand ridges	former wing(s)	parallel or slightly converging sand ridges	define transverse limit of former parabolic dune	former wings detached by migration of dune head	low	moderate to high	average	recurrent-drought
	border ridges	long sand ridge, straight or slightly sinuous, irregular crest-lines, divergent downwind	edges of deflation area or outer limit of dune occurrences	accumulation of sand by transverse winds from the deflation area	low-moderate	low-high	average - shallow	extended-droought
	deflation-front ridge	semi-arcuate irregular ridge without slipface	downwind edge of deflation area	dunes without slipface coalescing in front of their merged blowout depressions	low	low-high	average	extended drought
Dune blanket	large assemblage of dunes	often but not always chaotic assemblage of dunes with, large deflation area; may overlie older dunes	areas of ample sediment supply	area of dunes which have migrated as a group over formerly stabilized dunes	high	low-moderate	deep - average	renewed local activity
Sand sheet		low relief, varying thickness, thins away from source, lobate in plan view downwind from source	locally around dunes and regionally around dune areas	windblown sand of varying thickness around dunes; mostly niveo-eolian in origin	low-moderate	increasing away from source	deep - shallow	winter winds
Dune tongue		lobate body formed by sand sheets, transverse ridges and parabolic dunes; limited by converging border ridges	extends downwind from a major dune area	accumulation of windblown sand over generally nonsandy deposits	low-moderate	low	deep - shallow	extended drought

[1] All features described form parts of the parabolic dune association.

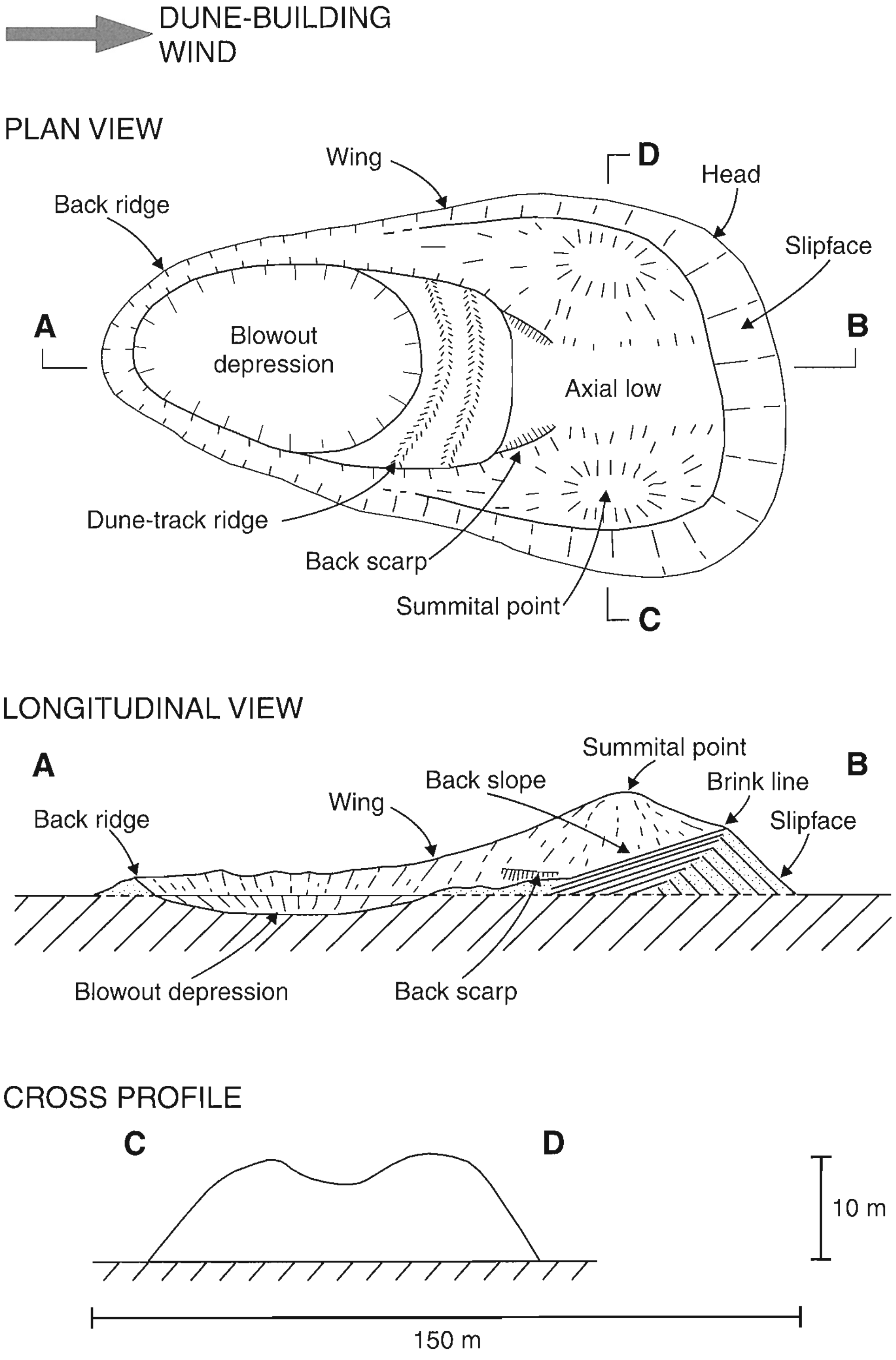


Figure 16. *Morphological attributes of a parabolic dune. Direction of dune-building wind refers to longitudinal and plan views. Modified from David (1988).*

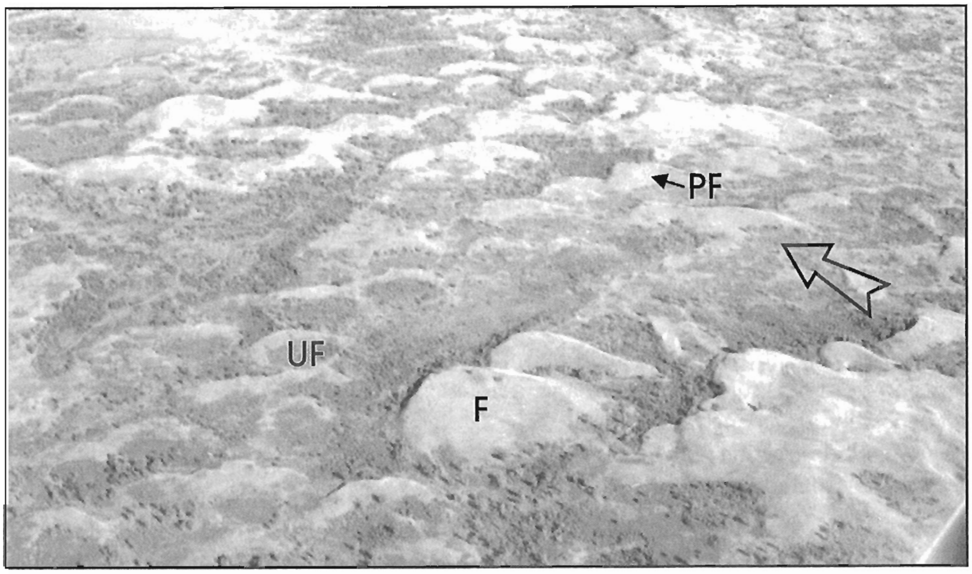


Figure 17. *Parabolic dunes in southern part of Great Sand Hills. Types include filled (F), partially filled (PF), and unfilled (UF); most are open (do not have a back ridge). Open arrow denotes direction of dune-building winds. View towards the east-southeast. Photo courtesy of P.P. David.*

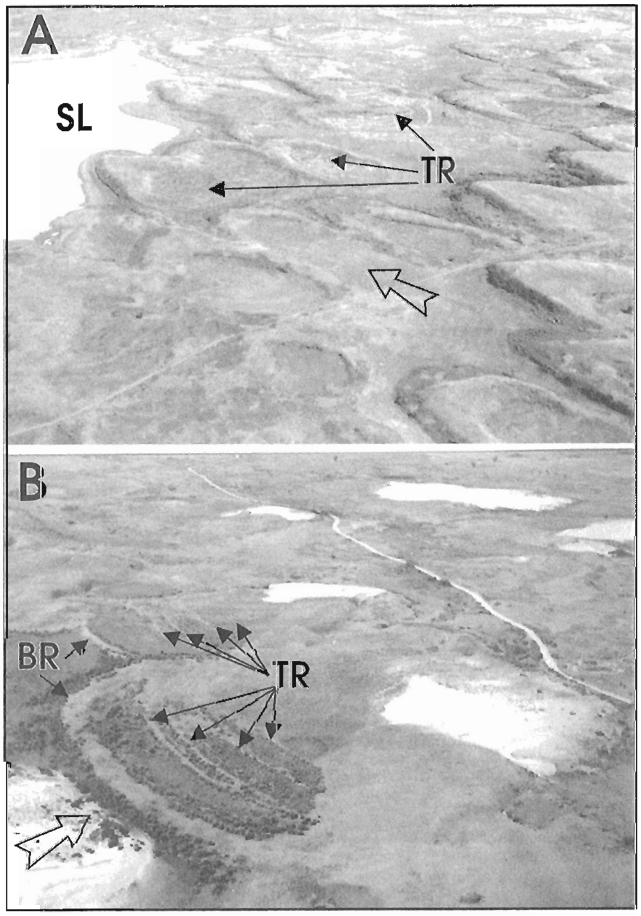


Figure 18*.*

Back ridges and dune-track ridges, open arrows denote direction of dune-building winds. ***A)*** *Multiple dune-track ridges (TR) occur within parabolic dunes near saline lake (SL), but are absent from dunes on higher ground at the right edge of photo. Crane Lake Sand Hills, view to southeast.* ***B)*** *Partially reactivated and stabilized parabolic dunes with exceptionally well developed, hummocky, back ridges (BR) and smooth dune-track ridges (TR). The dunes feature the same number and arrangement of ridges, indicating synchronous origin. In low-lying area of Seward Sand Hills, view to north. Photos courtesy of P.P. David.*

included in Table 1), forming well defined patterns (Fig. 20) that differ from compound dunes (McKee, 1979; cf. Smith, 1963).

A short-term change in prevailing wind direction may deform a parabolic dune into a **shield dune** (not to be confused with '*dune en bouclier*'; Högbom, 1923; Aufrère, 1931), that features a straight slipface with a semicircular stoss side defined, in part, by the back ridge (David, 1964). The highest point of the dune lies near the centre of the frontal slope which has a markedly different orientation than the original direction of sand transport. Shield dunes develop through erosion from the proximal wing of a parabolic dune, with redeposition occurring on the distal wing in response to the new wind direction. Shield dunes with steep frontal slopes facing southeastward are particularly well developed in the Westerham Sand Hills (Fig. 13, 21), amidst stabilized parabolic dunes oriented northeast (original sand transport direction). The suite of forms present (parabolic dunes, shield dunes, and transitional forms) suggests that some dunes were completely or partially stabilized prior to the deformation produced by the change in wind direction. The preservation of a large number of shield dunes indicates that stabilization subsequent to dune deformation was rapid. In other areas, individual shield dunes may also be found amongst otherwise undeformed parabolic dunes. Their presence may be explained in two ways. Either only one dune was active at the time the prevailing wind direction changed (suggesting the other dunes were largely stabilized), or the anomalous dune stabilized rapidly following deformation, while others remained active and regained their original parabolic form. Determining which of these alternatives occurred is possible only when absolute dates are available (e.g. Wolfe et al., 1995).

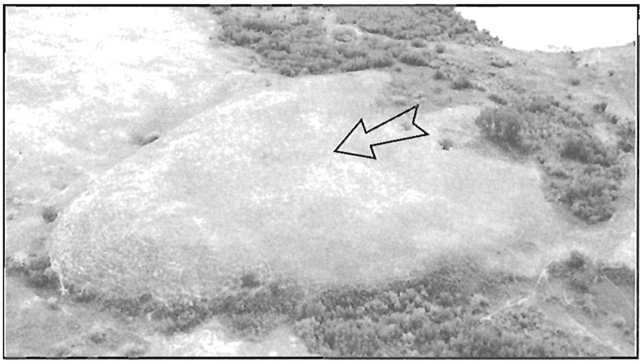


Figure 19. Stabilized, filled parabolic dune, Burstall Sand Hills. Open arrow denotes direction of dune-building winds. Photo courtesy of P.P. David.

Reactivation of partially or completely stabilized parabolic dunes may produce **ridge-sided**, or low-front dunes, that have well developed, fully active sand ridges on both sides of the head. These ridges are not simply over-developed wings, because they are not in aerodynamic union with the rest of the dune. Rather, they are relict features that became strongly modified when the dune head was reactivated. As on most eolian ridges, ridge slope angles are directly related to ridge height (David, 1981b), yet tend to cluster near either 20° or 34°. Ridge-sided dunes are well developed in the northwest part of the Great Sand Hills, and have been monitored for over three decades. This long-term monitoring shows that they are strongly influenced by southerly side winds.

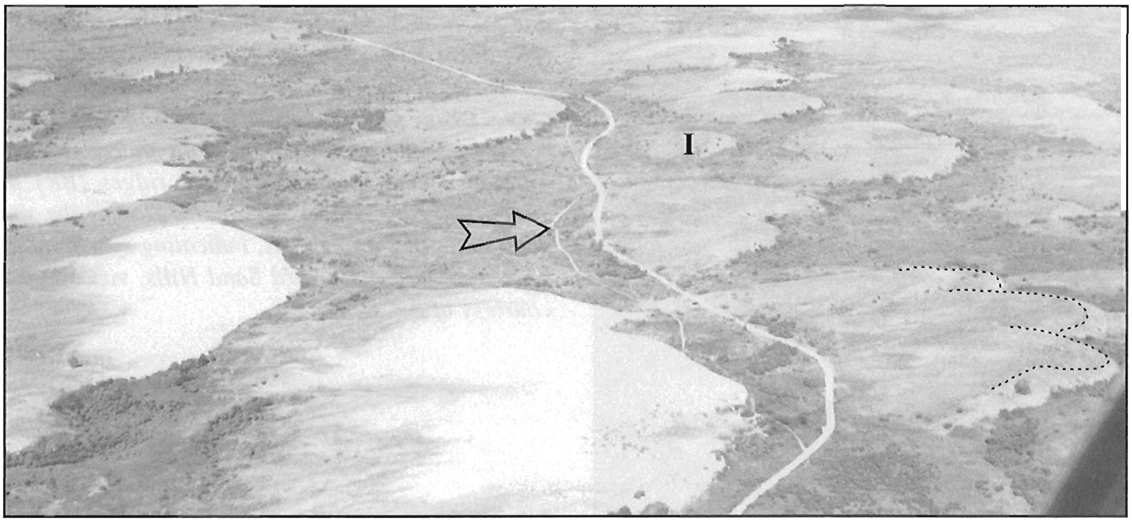


Figure 20. Partly active and stabilized composite dunes with an in-line arrangement, northwestern Great Sand Hills. Dashed lines on lower right outline three parabolic dunes that make up a composite dune. Dune in centre front is same as in Figure 24. A few individual dunes (I) are also visible. Open arrow denotes direction of dune-forming winds, view to north. Photo courtesy of P.P. David.

Blowout features represent a second major category of eolian sand phenomena. They occur either as primary features in areas of limited sediment supply, or the products of sporadic activity in areas of stabilized or partially stabilized parabolic dunes. Blowout features include both erosional landforms, ranging in scale from small **windpits** to large **blowout areas**, and depositional features in the form of **blowout ridges** and **blowout dunes** (Fig. 22). Blowout ridges are low, arcuate, and concave upwind, occurring in areas of limited sand supply. Although they may develop a low slipface, it generally is not preserved due to the low ridge height and deforming side winds. Blowout ridges are dominant eolian features in areas where surficial material is a thin veneer of sand, such as the Rolling Hills, Retlaw, Verger, and Kirkpatrick Lake areas of Alberta (Fig. 13). Blowout dunes are analogous to blowout ridges, but form in areas of moderate to high sand supply through the accumulation of sand on the lee side of a blowout depression. Blowout dunes are parabolic, but tend to feature multiple slipfaces, producing a more chaotic morphology than is typical of a simple parabolic dune.

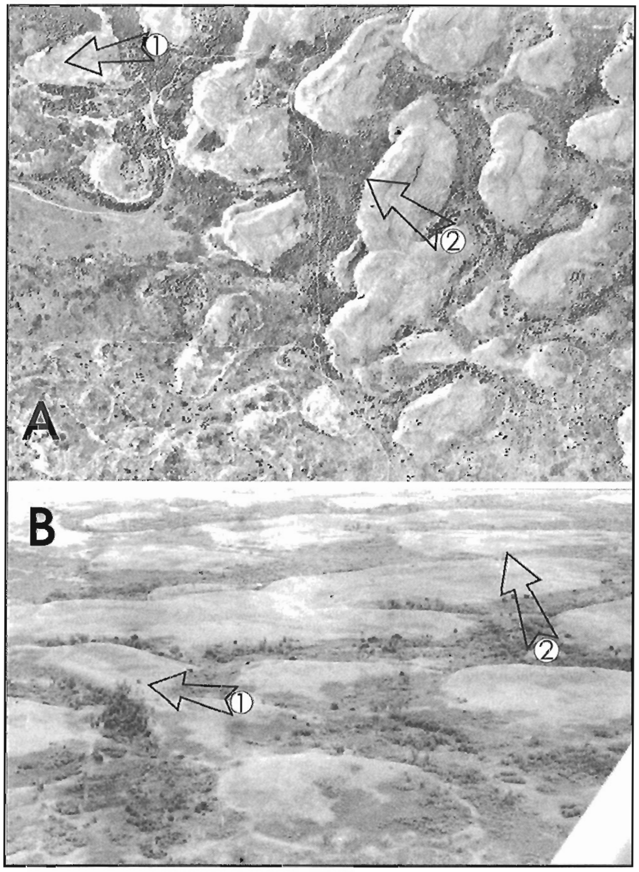


Figure 21. *Shield dunes, indicative of a change in the direction of dune-building winds, Westerham Sand Hills.* ***A)*** *Vertical airphoto showing original parabolic and reoriented shield dunes. Original dune migration is towards 80° (arrow 1), best shown by parabolic dune in upper left corner. The slipface of shield dunes is oriented 120-135° (arrow 2). Note transitional forms. NAPL A17661-120* ***B)*** *Oblique airphoto looking southeast, diagonally across area shown in photograph A. Original direction of dune migration was towards the left (arrow 1). Shield dunes are in upper two-thirds of photo, migration towards top of photo (arrow 2). Photo courtesy of P.P. David.*

In addition to **back ridges** and **dune-track ridges**, the parabolic dune association includes a variety of other sand ridges found alongside dunes. **Border ridges** are formed at the edge of dune fields or **deflation areas** by slightly divergent wind directions. In the latter, they generally diverge downwind, eventually merging with parabolic dunes on the downwind end of the deflation area. **Former wings** of parabolic dunes may become detached through stabilization or during partial reactivation of a stabilized dune, where the dune head continues to migrate even though the wings are stabilized (McKee, 1979). **Deflation-front ridges** are stabilized arcuate ridges occurring within or at the downwind edge of a deflation area. They are generally irregular in plan view, with an asymmetric profile (steeper lee side). The lack of steep frontal slipfaces reflects either low sediment supply or deflation by cross-winds. Deflation-front ridges are found only on nonsandy substrates, where a limited sand source has been deflated into small coalescent dunes by multidirectional winds. Deflation-front ridges are not common in the Palliser Triangle, but the best examples are found in eastern parts of the Bigstick-Crane Lakes Sand Hills (Fig. 13) overlying till (David, 1964).

Dune blanket is the term applied to a group of dunes that ‘overrun’ formerly stabilized dunes, a process which may, in turn, remobilize the overrun dunes. The superposition of two generations of sand dunes produces a chaotic topography, although individual dunes remain recognizable. Dune blankets appear to be quite widespread in the Palliser Triangle and have been found in association with signs of past human occupation, suggesting that dune activity may have been anthropogenically triggered.

Dune tongues are prominent downwind extensions of dune areas, delineated by downwind-converging border ridges, that develop during extended periods of eolian activity. Eventually, dune tongues may overrun older eolian sediments, such as sand sheets or loess. Dune tongues are typically composed of sand dunes of varied sizes, separated by deflated surfaces or a thin (< 1 m) sheet sand. If a dune area is laterally constrained, it may take the shape of a dune tongue, such as the classic example of the Tunstall Sand Hills area (Fig. 13). If the source area is elongated transverse to the dune-forming winds, several dune tongues may develop, such as those emanating from the eastern edge of the Great Sand Hills (Fig. 13; David, 1993).

A final important eolian feature is **sand sheets**, areas of variable sand thickness that generally thin downwind and lack significant relief. Sand sheets may accumulate in several ways: 1) in the form of aprons located at the downwind base of individual dunes, where niveo-eolian processes are important in their formation; 2) as patchy mantles over interdune areas; or 3) as regionally extensive blankets thinning downwind from dune occurrences, forming an intermediate facies between sand dunes and loess deposits.

Stabilization of sand dunes

A stabilized sand dune has a complete vegetation cover that effectively prevents wind erosion. Under temperate climates a vegetation cover is always present between adjacent dunes; however, it can only develop on the surface of active dunes if there is sufficient moisture in the dunes themselves. Because the removal or establishment of vegetation is not instantaneous, stabilization and reactivation of dunes will always lag behind climate-forcing events (David, 1995b). Moreover, stabilization rates are not uniform across the prairies. A dune will be stabilized more rapidly in the parkland regions peripheral to the Palliser Triangle than in the dry, grass-covered landscapes that characterize the Brown Chernozemic Soil Zone.

Today, active dunes are uncommon and unevenly distributed in sand hill areas of the Palliser Triangle. Aerial photographs show that eolian activity declined from the 1940s to the 1980s as a result of relatively humid climatic conditions promoting increased vegetation cover. In some areas, active sand surfaces expanded markedly in rapid response to the drought years of the 1980s (cf. Wolfe, 1995).

The rate and style of dune stabilization depends on prevailing climate and the ability of the dune sand and underlying sediments to absorb and retain moisture. The prevailing climate determines the rate and form of moisture input (rain and snow), while moisture retention depends largely on grain size, even among sandy deposits. Much of

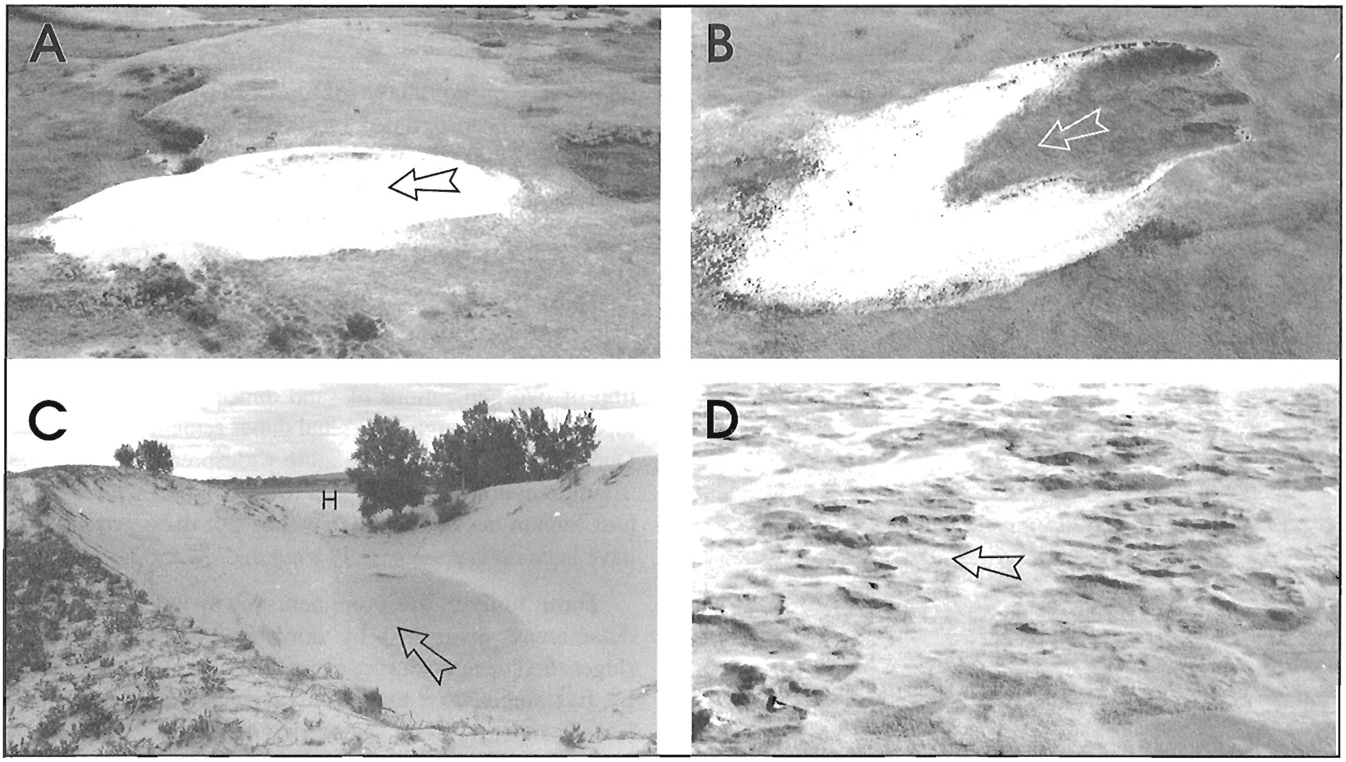


Figure 22. Active and stabilized blowout features, open arrows denote direction of dune-forming winds. ***A)*** *Active blowout dune that has developed from a dune crevasse in the head of a stabilized composite dune. Burstall Sand Hills, view to south.* ***B)*** *Blowout dune that remains attached to multiple blowout depressions. Tunstall Sand Hills, view south-southwest.* ***C)*** *View into blowout depression of active blowout dune that has developed from a formerly stabilized parabolic dune. The head of the former dune has been destroyed, while the head of the blowout dune in visible to left of trees (H). Vegetation on left wing has been recently been covered with sand moved by cross-winds. Flat floor of blowout depression is controlled by groundwater and coarsening grain size. Southern Great Sand Hills, view to east.* ***D)*** *Shallow blowout depressions surrounded by low blowout ridges, developed on formerly stabilized coarse-grained sediments. Bigstick-Crane Lake Sand Hills, view south-southwest. Photos courtesy of P.P. David.*

the moisture in active sand dunes is recharged by the melting of snow accumulated on the lee side of the dunes. If the spring melt is slow, it can recharge both the frontal part of the dune and sediments beneath the dune. During dry summer months, dunes lose moisture through evaporation, producing a sheet of dry sand on its exposed surface (i.e. the active layer). With strong winds, all the dry sand may be transported to the slipface, exposing moist sand at the dune surface for as long as the winds continue. Although this recently exposed moist sand will eventually dry and be transported downwind, its removal will occur at a much reduced rate. However, strong winds are often associated with frontal systems and rain storms that impede drying of the dune surface. With gentle winds, the active layer may increase in thickness and small bedforms, including miniature barchan dunes and transverse ridges, may develop in it (Fig. 23). Subsequent rain will stabilize those forms and, if the rain is very intense, surface runoff may be generated on the dune. On the slipface, the weight of the upper rain-moistened sand may surpass the shear strength of the underlying dry sand, causing the moist sand to slide and fissure. A low-intensity rain will help re-establish the original water content of the sand in the active layer.

Differences in grain size and associated moisture retention capacity produce differences in the rates and styles of dune stabilization, with vegetation colonization occurring most uniformly on relatively fine-grained sand dunes. Both the type and rate of vegetation colonization are influenced by site location. At the dune front, vegetation is generally abundant, owing to groundwater recharge from snow melt; however, vegetation here will be buried as the dune migrates forward (Fig. 24). At the base of the wings, vegetation also benefits from groundwater recharge by snow melt and, since it receives less blown sand than the dune front, is a more likely site for initial colonization of the dune surface. Vegetation at the back of a dune comprises grasses and other small herbaceous plants that invade blowout depressions, and this assemblage appears to advance at roughly the same rate as the dune itself. On occasion, large parts of a dune may remain unvegetated and yet become immobile, owing to protection by tall off-dune vegetation that inhibits sand transport long before final stabilization occurs. Once vegetation is established over parts of a dune through a subsurface system of rhizomes (*Psoralea lanceolata* and *Rumex venosus*), and through seed germination (various grasses), it hinders sand movement by increasing surface roughness (Fig. 24). If there is no sediment transported to the site to bury the colonizing vegetation, the sand surface will stabilize rapidly. Vegetation cover on a dune can fluctuate dramatically depending on moisture availability, but is minimal during exceptionally dry years. However, deeply buried roots remain protected for a long time and, unless exposed and destroyed by deflation, can rapidly regenerate the vegetation cover if dune moisture is adequate.

Climatic significance of parabolic dunes

The morphological characteristics of stabilized parabolic dunes are the result of a specific sequence of selectively preserved past climatic conditions. Because individual dunes may preserve this record of climatically triggered modification somewhat differently, they are powerful proxies of past climatically forced environmental change. Parabolic dunes are more likely to contain evidence of short-term climate fluctuations than would mobile desert (dry-sand) dunes, which may adjust completely to changed

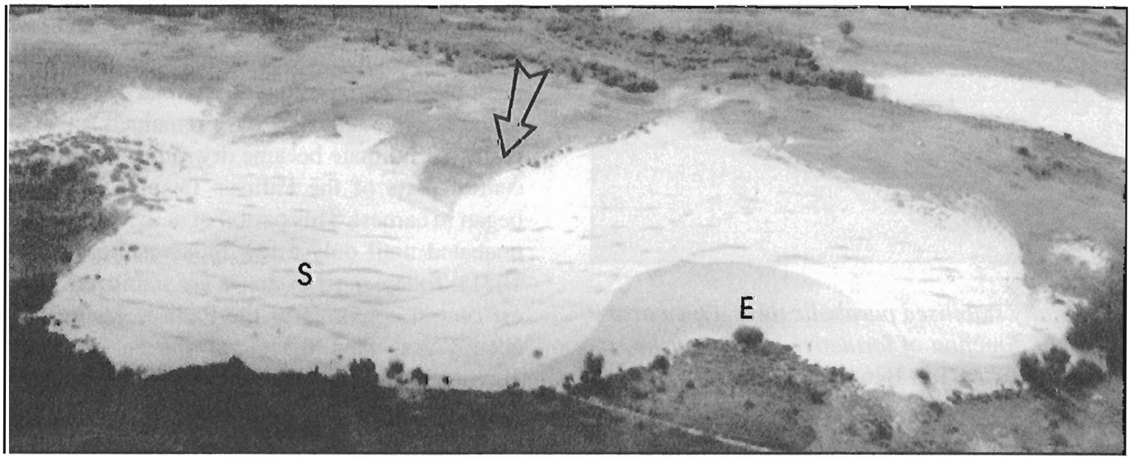


Figure 23. *Concave embayment on 16 m high slipface of composite dune (E), resembling barchanoid form. Embayment developed between joined parabolic dunes. Note trail buried by dune and secondary transverse bedforms (S) in active layer on head of dune, some of which are true barchanoid features. Open arrow denotes direction of dune-forming winds; northwestern Great Sand Hills, view west. Photo courtesy of P.P. David.*

conditions and leave no record of past conditions. In contrast, the palimpsest nature of the subhumid eolian landscape does not erase all proxy evidence of past climate among stabilized parabolic dunes. With regard to long-term climatic change, the presence of parabolic dunes themselves is proxy evidence of subhumid to semiarid conditions with sufficient annual moisture to maintain subsurface eolian sands in a moist state. Typically, dune sands in the Palliser Triangle have moisture contents of between 4 and 8%.

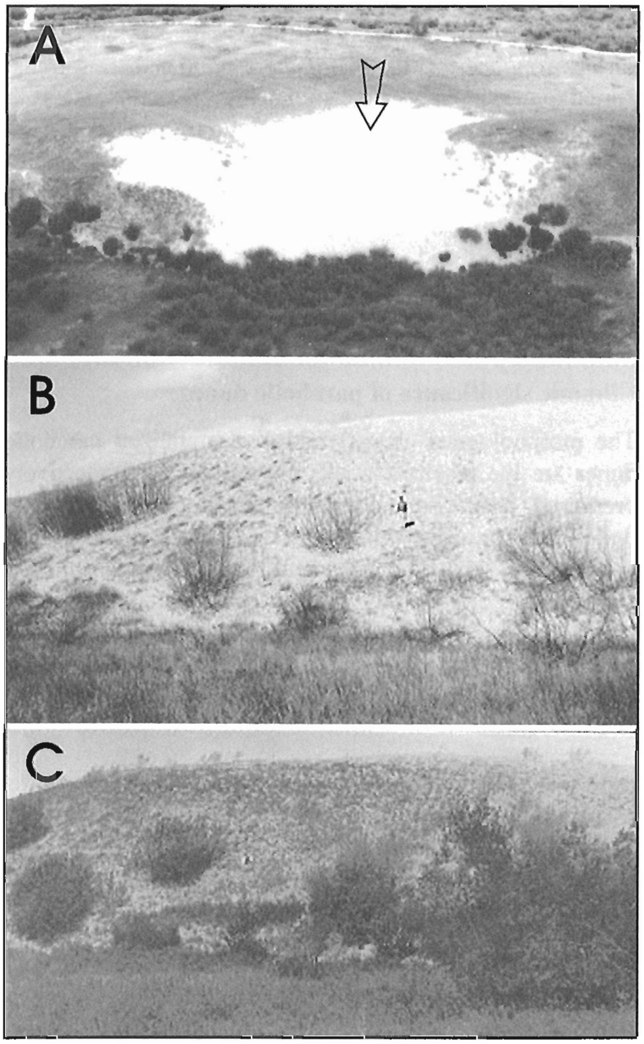


Figure 24. Partially stabilized parabolic dune. Open arrow denotes dominant direction of formative winds, northwestern Great Sand Hills. ***A)*** Tall Betula occidentalis *bushes in front of dune protect lower slipface from erosion by crosswinds.* ***B)*** *and* ***C)*** *expanding vegetation that reappears yearly on frontal slope (left side on photograph A) encroaches on active parts during moist years. Note change in type of stabilizing vegetation from left (complete cover and large bunch grasses) to right (mainly* Psoralea lanceolata *to active sand). Dune became stabilized a few years later. Photos courtesy of P.P. David.*

In addition to the morphological characteristics of individual dunes, the nature of a dune area itself provides information on the past climatic regime under which the dunes initially formed, as well as subsequent climatic changes. Although reconstruction of older sand-dune landscapes is difficult, detailed morphological analysis can provide evidence of a formative sequence that contains clues regarding past climate. Unfortunately, direct correlation of eolian deposits with independent proxy climate records is not straightforward because absolute dating opportunities are limited in eolian deposits. This is particularly true for sand dunes, where paleosols and other concentrations of organic matter are rare. Optical dating of sand grains (e.g. Aitken, 1992; Wolfe et al., 1995) offers a means of overcoming this major limitation.

The three conditions necessary for eolian activity: sediment supply, sufficiently strong winds, and a locally sparse to absent vegetation cover, existed on a regional scale in the Palliser Triangle during Late Wisconsinan deglaciation. At this time, the first dunes may have been formed by dry adiabatic winds emanating from the retreating Laurentide Ice Sheet (David, 1981b, 1988), though these southeasterly winds must have been of relatively short duration. These formative winds strongly contrasted to the modern westerly prevailing winds, and as a result, dunes formed at this time would have had different orientations from those of today (David, 1981b, cf. Kutzbach and Wright, 1985). Furthermore, it is possible that these original dunes in the Palliser Triangle may have been dry-sand transverse dunes (David, 1977a) that were subsequently transformed into parabolic dunes as moisture availability increased.

Following deglaciation, dunes were active and sheet sand and loess began forming as soon as source deposits were exposed. This activity was briefly interrupted by a humid period just before 10 ka (David, 1972, 1995a) that facilitated development of an extensive vegetation cover, thereby reducing eolian activity and promoting development of soil horizons on most eolian deposits (though many of the larger dunes may have remained active). In the early Holocene, climate became dry quite abruptly, in at least the central parts of the Palliser Triangle, and eolian activity began in earnest. This period of activity may have continued unabated until only a few thousand years ago (cf. David, 1971). Today, most of dunes are stabilized. Even in the driest central core area of the Palliser Triangle, active dunes occupy less than 0.5 % of the surface area (Epp and Townley-Smith, 1980). Moreover, although dune activity remains climatically influenced, much of the recent activity may have been triggered by human disturbance (David, 1993).

Regional, late-Holocene dune stabilization was a gradual event, beginning with smaller dunes and culminating with larger ones that remained active for a considerably longer time (cf. David, 1971). Under present climatic conditions, relatively minor changes in yearly weather conditions can affect dune activity in the region (Wolfe et al., 1995). Changes in the extent of activity, and in dune morphology, may occur within a few years in response to short-term climatic fluctuations (David, 1981a). If, for example, humidity increases, active dunes will either stabilize (thereby preserving their primary form) or remain active and develop secondary features. If the region becomes more arid, the dunes may transform to other dune types (David, 1977a, p. 141-145). If all the dunes in an area do not stabilize at the same time, then a mixture of dune forms will coexist. Therefore, to avoid misinterpreting prevailing dune forms and processes, a clear temporal perspective on landform evolution must be maintained.

The shift from extensive eolian activity during the mid-Holocene warm interval to gradual stabilization of dune areas during the late Holocene, associated with a change to a cooler and wetter climate (cf. Vance et al., 1995), provides important information for landscape responses under a climatic warming scenario. As such, more exact and succinct data on dune responses to climate change over the last 5000 years are required. Data from areas beyond the margin of the Palliser Triangle (David, 1971) confirm that a gradual decrease in eolian activity occurred during this period, although the trend was repeatedly interrupted by localized activity. Other evidence from further south on the Great Plains (e.g. Madole, 1994) also supports these observations. The changes in extent of eolian activity caused by modern weather fluctuations (Wolfe et al., 1995), as well as the greater extent of activity during the past 200 years, documented in both historical accounts (Muhs and Holliday, 1995) and optical dating of dunes sands from within the Palliser Triangle (Wolfe et al., 1995), all convincingly suggest that much of the Great Plains lies near a threshold of widespread eolian activity (Madole, 1994). Better documentation of these past climatic triggers will improve understanding of the potential effects of future climatic changes. The magnitude and exact nature of these triggers should be the focus of continued research.

THE FLUVIAL SYSTEM

I.A. Campbell

Introduction

The pattern, nature, and products of fluvial erosion in the Palliser Triangle reflect the interaction of four major controls: climate (especially amount and distribution of precipitation); geology and topography; the organization of the drainage network; and, to an increasing degree, the effects of human activities. These controls and their associated landscape components (slopes, soils, vegetation, and land-use) have produced great variability in the regional landscape which reflects, in part, the relative efficacy of fluvial processes. Some of Canada's most dramatically water-eroded landforms (Campbell, 1987) and highest sediment-carrying drainage basins (Stichling, 1973), are adjacent to vast areas where there is little or no evidence of contemporary fluvial activity (Fig. 25) and in which the threat of water erosion on agricultural land is regarded as moderate (Coote et al., 1981) to negligible (Tajek et al., 1985).

The following discussion describes the characteristics and origin of the fluvial system in the Palliser Triangle as they relate to the above-mentioned controls. This overview is followed by a more detailed discussion of the spatial patterns of runoff and sediment generation as they relate to the major through-flowing drainages. It is the assertion of the author that the few previous studies of regional erosion rates grossly overestimate the size of the areas which effectively contribute sediment to these major drainages, leaving an erroneous impression of the importance of fluvial erosion. These previous studies are contrasted with a simple, but geomorphologically more appropriate analysis of contributing areas, which leads to the conclusion the vast majority of the Palliser Triangle is largely inactive with respect to fluvial erosion. This analysis only considers delivery of sediment to through-flowing rivers, and the conclusions do not necessarily apply to water erosion of agricultural lands, which is discussed elsewhere in this report (see "Soil Redistribution"). Finally a brief review of Holocene fluvial geomorphology is presented together with an evaluation of the potential response of fluvial systems to climate change.

Drainage systems

The South Saskatchewan River and its three main tributaries, the Red Deer, Bow, and Oldman rivers, form the dominant through-flowing drainage system in the Palliser Triangle (Fig. 2, 26). These major rivers derive about 70% of their mean annual discharge from snowmelt in the Rocky Mountains to the west. Of the South Saskatchewan River's mean annual total flow of 8.07×10^6 dam^3 recorded at Lemsford, Saskatchewan (Fig. 26, Table 2), the net increase (absolute inflow minus consumptive usage; see "Human influences", below) within the boundaries of the Palliser Triangle is only about 15%.

No major rivers have their source areas within the Palliser Triangle. Swift Current Creek, which heads in the eastern Cypress Hills, is the only major stream that joins the South Saskatchewan system outside Alberta. The Milk River is the only other through-flowing river system (Fig. 2, 26), and it drains only extreme southern Alberta and southwestern Saskatchewan. Most major tributaries of the Milk River outside Alberta head in the Cypress Hills (e.g. Frenchman River, Lodge and Battle creeks), while numerous smaller tributaries tend to be intermittent. The extreme eastern area of the Palliser Triangle is part of the Souris River basin. Much of the Palliser Triangle (as defined previously) is internally drained (Table 3), and contributes neither water nor sediment to the through-flowing drainage system. These extensive areas of internal drainage lie mostly in low-relief areas of Saskatchewan, but include extensive areas of hummocky moraine and sand dunes.

Origin

The main drainage system of the Palliser Triangle has developed from a network of Late Pleistocene subaerial and subglacial meltwater channels that crossed topographic divides, excavated and reoccupied preglacial valleys, and cut entirely new channels (e.g. Klassen, 1994). Most models of meltwater channel formation in the region, and adjacent areas (e.g. St-Onge, 1972; Stalker, 1973; Kehew and Lord, 1986; Teller, 1987), largely ascribe their origin to subaerial processes associated with drainage of proglacial lakes. Hence channel evolution is closely linked to former ice margins of the retreating Laurentide Ice Sheet (Klassen, 1989, 1994). None of these models consider the potential effects of hypothesized catastrophic subglacial meltwater floods (Rains et al., 1993), which, if correct, would obfuscate linkages between channels and ice-marginal positions. It is also possible some lakes associated with these channels were subglacial rather than proglacial. Therefore many details concerning the nature, timing, and sequential development of channels that form the basis of the present drainage network remain largely unknown.

The postglacial evolution of the Palliser Triangle drainage system has been affected by both climatic changes (discussed later in this section) and changes in base level caused by glacioisostatic adjustments. Differential postglacial rebound has caused streams to incise the southern prairies by lowering their relative base levels (Kugler and St-Onge, 1973); unfortunately the magnitude of rebound is difficult to quantify in continental regions (e.g. Andrews and Peltier, 1989). Scott (1971) reported 60 m of differential rebound along a 100 km section of the South Saskatchewan River, a value that is consistent with geophysical modelling of a thin ice sheet with a low surface profile (cf. Walcott, 1970; Matthews, 1974; Rains et al., 1990).

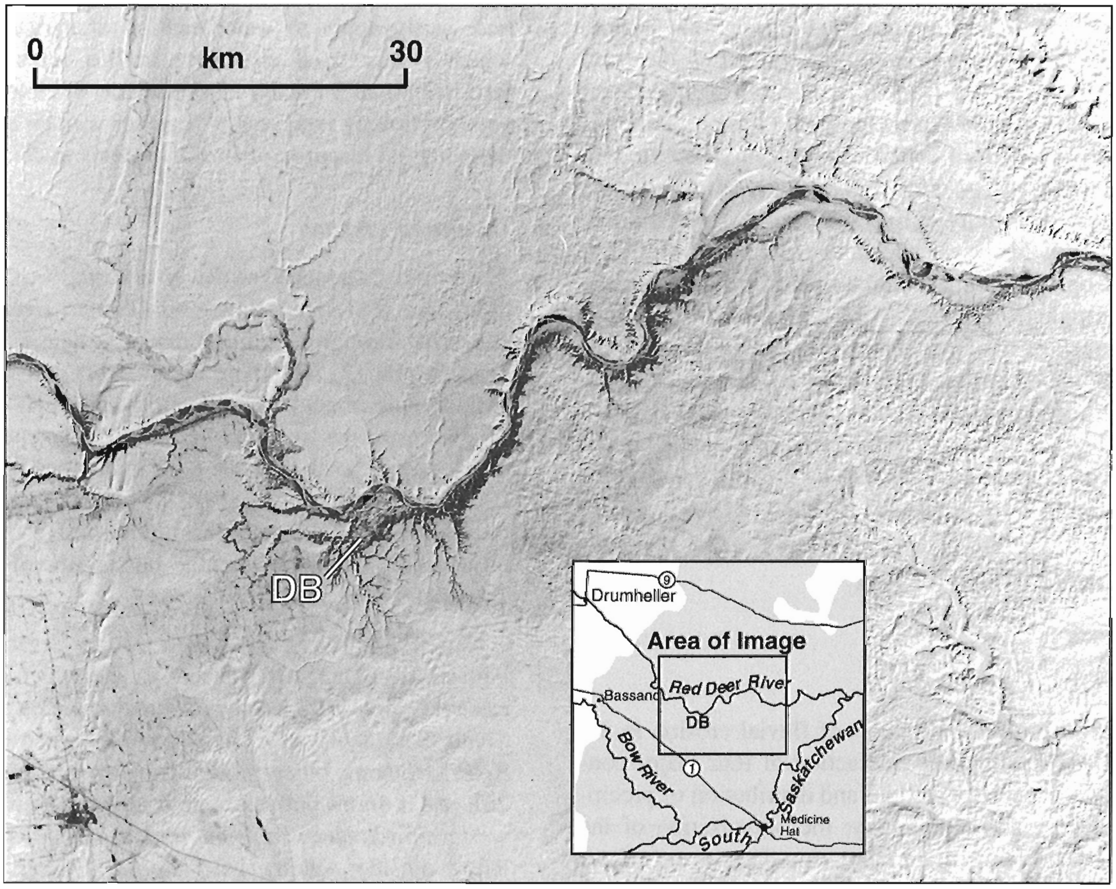


Figure 25. Landsat multispectral scanner (MSS) image of part of the lower Red Deer River. DB denotes Dinosaur Badlands, which are contained within Dinosaur Provincial Park. The major source areas for sediment entering the river consist of a network of giant gullies with an average length of around 1 km. Most of the prairie surface drains to internal basins, contributing neither water nor sediment to the through-flowing river. The town of Brooks, Alberta is visible in the lower left corner.

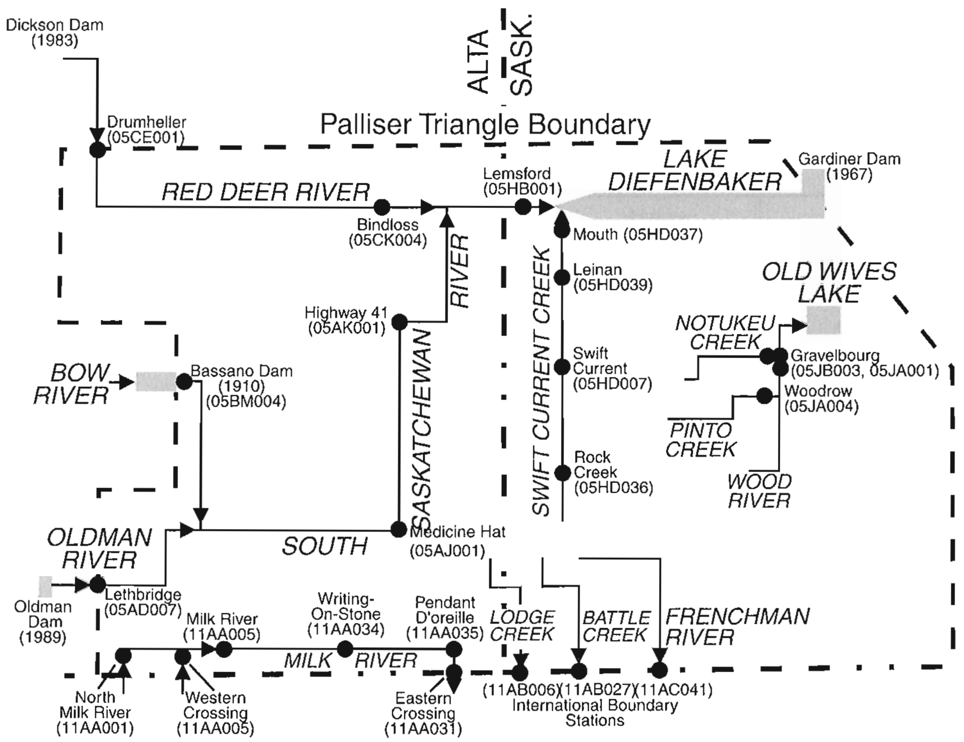


Figure 26.

Schematic representation of Palliser Triangle drainage systems (compare with Fig. 2). Recording stations are identified by name and Water Survey of Canada number. Shaded areas denote lakes or reservoirs.

Rapid postglacial incision (of the order of 50-100 m), was followed by a period of infilling within many channels throughout the Palliser Triangle. Various studies report postglacial fills 25-80 m thick (e.g. McPherson, 1968; Klassen, 1975; Bradley, 1982; Christiansen and Sauer, 1988). This fill is largely derived from the rapid valley-side erosion (see "Mass Wasting Processes") that introduced large volumes of sediment into the adjacent streams, causing widespread valley alluviation and subsequent phases of aggradation and degradation during the Holocene (O'Hara and Campbell, 1993). Although rates of early Holocene valley incision remain largely unknown, they appear to have been fairly rapid; Rains et al. (1994) suggested that about 25 m of downcutting occurred in the Drumheller region of the Red Deer River valley over approximately 4000 to 5000 years. It has been demonstrated that most of the badlands erosion along the lower Red Deer occurred well before 4.4-6.2 ka BP (Bryan et al., 1987), and in Little Sandhills Creek (a tributary to the lower Red Deer River), over 20 m of incision occurred in less than 7000 years (Campbell and Evans, 1990).

Table 2. Mean annual total discharge and incremental downstream contributions for main drainage systems in the Palliser Triangle[1].

RIVER / stations	Mean annual total discharge (dam^3 x 10^6)	Incremental downstream increase (dam^3 x 10^6)
RED DEER		
Drumheller	1.68	
Bindloss	1.80	0.12
SOUTH SASKATCHEWAN		
Medicine Hat	5.10	0.03
Highway 41	5.18	0.08
Lemsford	8.07	1.09[2]
BOW		
below Bassano Dam	2.52	
near mouth	2.86	0.34
OLDMAN		
Lethbridge	2.63	
near mouth	2.21	-0.42[3]
MILK RIVER		
Western Crossing	0.06	
Milk River townsite	0.28	0.22
Eastern Crossing	0.31	0.03
SWIFT CURRENT CREEK		
Rock Creek	0.02	
near Leinan	0.03	0.01
near mouth	0.08	0.05

[1] Data from various lengths of record (Environment Canada 1989, 1991)

[2] Includes values from Highway 41 on the South Saskatchewan River and Bindloss on the Red Deer River

[3] Reduced discharge downstream reflects irrigation diversion

Climate

Climate is the main forcing function for most fluvial processes. The severe annual moisture deficit of the Palliser Triangle results in little runoff generation except where sporadic, high-intensity summer rainstorms occur in areas where topography and geology favour low infiltration losses. Such areas may or may not contribute runoff or sediment to through-flowing drainage channels. The wetter

Table 3. Areas of interior drainage within the Palliser Triangle[1].

Area	Hydrological Atlas of Canada (1978)		Last (1984)	
	area (km^2)	%	area (km^2)	%
Great Sand Hills	12 073	9.6	15 347	12.3
Southcentral Saskatchewan	23 247	18.6	23 573	18.8
Central Alberta/Saskatchewan	7 977	6.4	15 687	12.5
Milk River Ridge	3 693	2.9	n.d.	n.d.
Southern Saskatchewan	n.d.	n.d.	4 816	3.8
Total	**46 990**	**37.6**	**59 423**	**47.5**

n.d. - not defined in study.

[1] Calculated at 125 000 km^2 corresponding to the Brown Chernozemic Soil Group.

uplands of the Cypress Hills and their adjacent areas generate comparatively little discharge and contribute little runoff or sediment to the main drainage system (McPherson, 1975). Over much of the Palliser Triangle, mean annual surface runoff is less than 100 mm (Fisheries and Environment Canada, 1978), and large areas may produce less than 10 mm per annum (Ashmore, 1986).

While snowfall contributes about 25-40% of the mean annual precipitation on the prairies, it generates about 80% of prairie stream runoff (Gray, 1970) and is often the only major runoff source for small streams (Day, 1989). There is considerable interannual variation in snowfall contribution to streamflow, related to both the amount of precipitation and the frequency of ablation and sublimation events through winter (Maulé and Gray, 1994). Although snowfall is more evenly distributed than rainfall, redistribution by wind produces large local variations. Chinook winds are especially effective in reducing snowcover in the western Palliser Triangle, reducing the amount of snow cover available for spring runoff (Longley, 1972).

These climatic variations have major effects on runoff generation. The boundaries of areas contributing runoff in prairie drainage basins are very dynamic, displaying great interannual variability in response to precipitation and antecedent moisture conditions. Stichling and Blackwell (1958) examined a small tributary basin of the Assiniboine River in eastern Saskatchewan and determined that the actual runoff contributing area never exceeded 69% of the total basin (gross area), and in dry years the contributing area was reduced to 18% of the basin. Runoff volumes from 1916-1955 suggest that potential runoff can vary by almost 800% in prairie basins (Stichling and Blackwell, 1958).

Human influences

Large-scale European agricultural settlement in the Palliser Triangle, beginning in the late nineteenth century, has markedly affected the region's landscape and drainage system. Specific effects on fluvial processes are impossible to determine quantitatively, as there are no reliable discharge or sediment data for the presettlement period.

All main drainage systems in the Palliser Triangle, and most minor channels, have been dammed or flow-regulated to some extent, and large storage areas have been built. On the Milk River, dams and water-diversion projects have been constructed since the early 1900s. There are more than 440 000 ha of irrigated land in the Palliser Triangle, over 90% of which lies in Alberta (Statistics Canada, 1982). Thousands of kilometres of canals, ditches, and diversions have created a complex, wholly synthetic pattern of water flow and sediment transport about which little is known (Carson and Hudson, 1992). Many natural channels that would have carried only intermittent flow prior to settlement now move water and sediment for much of the year. Moreover, many of these channels integrate extensive areas of what were once internally drained networks into the through-flowing fluvial system. Intra- and interbasin transfer of water is practised on a wide scale. In Alberta's Eastern Irrigation District alone (one of fifteen such districts), the main diversion system links the Bow River to the Red Deer River through a network of canals whose total maximum flow capacity exceeds 180 $m^3 \cdot s^{-1}$, while its main reservoir (Lake Newell) has a capacity of more than 220 x 10^6 m^3. Much of the irrigation water is either consumed by crops or lost through evaporation and by seepage along the smaller, unlined ditches. In 1981, the average consumptive use of irrigation water in Alberta's St. Mary, Taber, Magrath, and Raymond irrigation districts was 3.5 $dam^3 \cdot ha^{-1}$ (Environment Canada, 1985). Extrapolation of this value to include all of Alberta's irrigated land within the Palliser Triangle yields a total consumptive use (in 1981) of about 1.4 x 10^6 dam^3. That amount exceeds the net increase in the total mean annual flow (1.24 x 10^6 dam^3) of the South Saskatchewan River within the Palliser Triangle (Table 2).

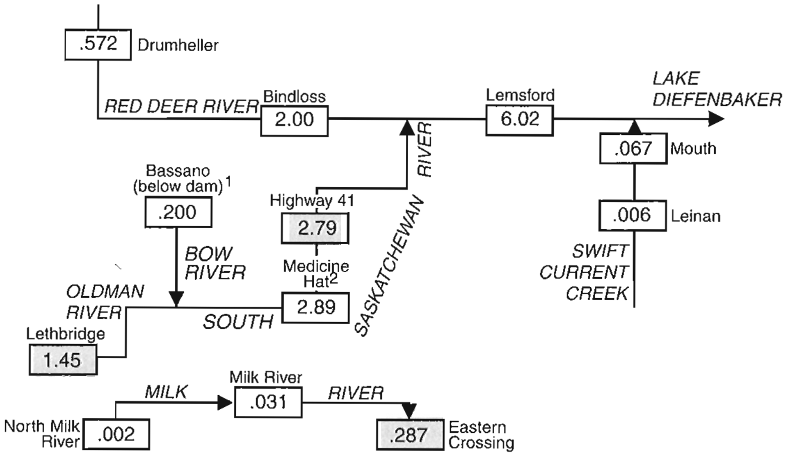


Figure 27.

Long-term mean seasonal (April-October) suspended-sediment loads (x 10^6 t) for stations used in this study. Data from Ashmore (1986); superscripts beside station names indicate: 1) estimated value and 2) corrected rating equation value.

Fluvial processes, sediment yields, and erosion rates

Fluvial erosion involves two distinct but related processes; runoff generation and sediment transport. The traditional tripartite model of the fluvial system, involving sediment production, transfer, and storage, assumes a close linkage between the areas of runoff generation and the sediment sources (Summerfield, 1991). Typically, this involves channel networks in the upper drainage basin that are integrated into larger channels in which discharge and sediment load are closely related, with most sediment deposition occurring on wide floodplains in the downstream section of the basin (Schumm, 1977b). This model is not appropriate for the major watersheds of the Palliser Triangle where the main runoff-generating regions and the major sediment source areas are widely separated. This disassociation of runoff and sediment source areas has a profound influence on how fluvial processes are expressed in the landscape and the way in which their effects are interpreted.

For the purposes of drainage-basin analysis in this study, the boundary of the Palliser Triangle includes gauging stations on the Red Deer River at Drumheller, on the Bow River at the Bassano dam-site, and at Lethbridge on the Oldman River. The South Saskatchewan drainage system is terminated at Lemsford (Fig. 26).

Sediment data

The most complete study of stream flow and sediment transport in the Palliser Triangle, the basic reference for the material presented here, focuses on the Saskatchewan River basin from the Rocky Mountains to western Manitoba (Ashmore, 1986). Additional information on the Milk River is provided by Spitzer (1988). To analyze streamflow, sediment transport, and yields, the Palliser Triangle area, as defined previously, is expanded slightly to include the cities of Drumheller on the Red Deer River and Lethbridge on the Oldman River. The main drainage system and mean seasonal (April-October) suspended-sediment loads are depicted schematically in Figure 27. Water Survey of Canada (WSC) sediment data is the only comprehensive and accessible source of information on sediment-yield patterns and, by extension, regional fluvial erosion. The quality of the data, scarcity of recording stations, and duration of observations all compromise the overall integrity of the data (cf. Ashmore, 1986). In particular, since the Milk River basin data encompass only very short periods (as little as one year), they must be considered only as speculative indicators of load conditions at best (Spitzer, 1988).

Table 4. Progressive, downstream, annual, suspended-sediment load increases for major drainage systems in the Palliser Triangle. Data from Ashmore (1986) and Spitzer (1988).

Stations	Load increase (x 10^6 t)
Drumheller-Bindloss	1.43
Bindloss+Highway 41-Lemsford	1.23
Medicine Hat-Highway 41	-0.10
Bassano+Lethbridge-Medicine Hat	1.24
Leinan-mouth of Swift Current Creek	0.061
North Milk River-Milk River	0.029
Milk River-Eastern Crossing	0.256

To evaluate sediment input to these drainages from Palliser Triangle landscapes (as opposed to regions to the west), suspended-sediment data are summarized in terms of downstream load increases between recording stations (Table 4). Boundary stations (Bassano, Drumheller, Lethbridge, and North Milk River) are regarded as having zero values. These data show a downstream increase in sediment load for all but one increment. The exception is for the South Saskatchewan River between Medicine Hat and Highway 41, where a minor decrease in sediment load is recorded, suggesting sediment storage (Ashmore, 1986). This corresponds to a stretch where there is no significant inflow between gauging stations (Table 2). Significant increases in sediment load predictably occur downstream of the confluence of major rivers (Red Deer and South Saskatchewan, Bow and Oldman; 1.23 and 1.24 x 10^6 $t{\cdot}a^{-1}$ respectively). However, the largest increase in sediment load (1.43 x 10^6 $t{\cdot}a^{-1}$) occurs along the Red Deer River between Drumheller and Bindloss. The fourth largest increase (0.256 x 10^6 $t{\cdot}a^{-1}$) occurs along the Milk River, downstream of the town of Milk River.

Sediment-yield data from tributary basins within the Palliser Triangle are scarce, but are sufficient to account for the dramatic increases in sediment load observed along the Red Deer and Milk rivers. Monitoring erosion rates and sediment yields in badlands regions of the Palliser Triangle indicates that extremely high sediment yields are produced from very small areas (e.g. Campbell, 1977; Barendregt and Ongley, 1977; Bryan and Campbell, 1980, 1986). Campbell (1992) showed that potential yields in the Red Deer badlands averaged 2500 $t{\cdot}km^{-2}{\cdot}a^{-1}$ (range 800 to >3000 $t{\cdot}km^{-2}{\cdot}a^{-1}$). Given the proximity of these sites to the Red Deer River, it is likely that most of this material is either transported directly into the river (between Drumheller and Bindloss) or is temporarily deposited on the river's floodplain (Campbell, 1992). Similarly, in the lower Milk River valley, Barendregt and Ongley (1977) estimated that about 111 x 10^3 t of sediment are produced by summer rainstorms alone over the approximately 260 km^2 of canyon they studied. One badland gully basin of 0.39 km^2 yielded about 560 t. Clearly these localized areas of badlands are major sediment sources that account for the pronounced increase in sediment load downstream of the town of Milk River, noted above.

The exceptionally high sediment yields from these badland areas is an example of the role of partial-area sediment contributions (Campbell, 1985), in which highly localized source areas exert a disproportionately large influence on the river's sediment load characteristics. Campbell (1973, 1977, 1992) demonstrated that a badland area of roughly 800 km^2 along the Red Deer River has the potential to supply all, or most of, the mean annual suspended-sediment load of about 2.00 x 10^6 t recorded at the Bindloss station. Ashmore (1992, 1993) confirmed that sediment data from the South Saskatchewan basin reflect the importance of highly erodible materials in close proximity to the channels and a general tendency for sediment loads to increase downstream. The pattern of downstream increase in sediment loads conflicts with the generally accepted model that specific sediment yields decrease as the basin area increases (reviews in Gregory and Walling, 1973; Schumm, 1977b; Walling and Webb, 1983; Graf, 1988).

Erosion rates

The distribution and intensity of fluvial erosion in a drainage basin may be assessed through calculation of regional erosion rates. Stream loads, averaged over the contributing basin, show sediment yield per unit area of basin. Rates are expressed either in volume/area/time (e.g. $m^3{\cdot}km^{-2}{\cdot}a^{-1}$) or in terms of surface lowering (e.g. $mm{\cdot}a^{-1}$). Erosion rates (E_r) are usually calculated as:

$$E_r = \frac{\textit{total load at a station}}{\textit{basin area x specific gravity of the sediment}}$$

Stichling (1973) and Slaymaker and McPherson (1973) analyzed sediment loads of various Canadian rivers to compare regional erosion (denudation) rates. Results relevant to the Palliser Triangle are summarized here as four subregions; western, central, eastern, and southern (Table 5). Although differences in techniques and the station records used preclude detailed comparisons between the two studies, both suggest that erosion rates decline in an easterly direction, and Stichling's (1973) analysis indicated that extremely high erosion rates are characteristic of the southern region. The critical weakness in both studies is that gross basin area was used. That is, it was assumed that the entire basin contributed water and sediment to the through-flowing rivers, in spite of the fact that sediment yield should only be calculated from areas of the basin that are producing sediment (Wigham and Stolte, 1973; Campbell, 1977).

Recognition that the use of gross basin area is inappropriate for calculation of regional erosional rates gives rise to the concept of effective contributing areas. Effective areas of prairie drainage basins are defined by the Prairie Farm Rehabilitation Administration (PFRA) as those areas that contribute runoff to main channels for a flood with a two-year return period (Prairie Farm Rehabilitation Administration, 1983). Noncontributing areas were identified as dead drainage areas, with gross drainage area being the sum of effective and dead areas. These areas, calculated from PFRA (1991) data, are presented for portions of the six major river basins in the Palliser Triangle: the Red Deer, Bow, Oldman, Milk, and South Saskatchewan rivers and Swift Current Creek; as well as for tributaries to the Milk River in southeastern Alberta and southern Saskatchewan, and the interior drainage into Old Wives Lake (Table 6).

Gross and effective areas differ considerably between drainage basins because of differences in basin size, shape, and topography. The mean percentage of effective to gross areas ranges from a maximum value of about 80% (tributaries to the Milk River) to a minimum of 45% (South Saskatchewan River). A recurrent trend in many basins is a marked decrease in the percentage effective area downstream. For example, Swift Current Creek exhibits a strong decrease in the relative size of its effective areas (76.1%; 68.9%; 51.8%, and 25.2%, respectively) as it increases in distance downstream from its steeper headwaters to its junction with the South Saskatchewan River in the drier plains.

Table 5. Mean annual denudation rates and suspended-sediment yields in the Palliser Triangle region.

Category and unit	Region[1]			
	Western	Central	Eastern	Southern
Slaymaker and McPherson (1973)				
Mean denudation (clastic load) $mm\cdot a^{-1}$	0.021-0.04	0.0051-0.01	<0.0013	n.a.
Mean denudation (dissolved solids) $mm\cdot a^{-1}$	0.0051- 0.01	0.0026-0.005	0.0013-0.0026	n.a.
Mean denudation (total) $mm\cdot a^{-1}$	0.021-0.04	0.011-0.02	0.0026-0.005	n.a.
Stichling (1973)				
Mean annual suspended sediment concentration (mg/L)	201->1000	0-50 to 401-700	0-200	>1000
Mean annual suspended sediment yield (mg/km^2)	46-227	<1.7 to 46-227	<1.7	n.a.

[1] Defined as: western - South Saskatchewan River drainage basin in Alberta; central - South Saskatchewan River drainage basin in Saskatchewan; eastern - Old Wives Lake drainage basin, including Wood River; southern - Milk River drainage basin in Alberta and Saskatchewan.
n.a. - not available

Use of effective contributing areas as defined by PFRA (1983, 1991), rather than gross areas, to calculate annual sediment yields (Table 7) results in very different patterns than those reported by Stichling (1973) and Slaymaker and McPherson (1973). However, the utility of these values may be questioned given the relatively low average yield (120 $t\cdot km^{-2}\cdot a^{-1}$) for the region as a whole compared with the field studies discussed previously of sediment yields from tributary basins. Even with further refinement of the definition of effective contributing areas to account for potential upstream sediment traps such as reservoirs, etc. (Ashmore, 1986), it is still apparent that the calculated effective contributing areas are considerably larger than those which actually deliver the vast majority of sediment. In most prairie rivers, sediment is primarily derived from the stream bed, banks, and valley sides in close proximity to the channel, as Ashmore (1986, p. 198; 1992; 1993) acknowledged. Similar conclusions were reached by Kellerhals et al. (1974), and by Carson and Hudson (1992).

Rather than defining effective areas in the manner discussed previously (Prairie Farm Rehabilitation Administration, 1991; Ashmore, 1986), it is proposed here that a more realistic approach would be to assume the effective sediment-yielding area is restricted to the river valley itself (channel length x mean valley width). For a first approximation, calculations are based on channel lengths measured from 1:250 000 scale NTS map sheets using a computing planimeter, and an assumed valley width of 2 km (Table 7). These values show a more coherent regional pattern than any of the previous calculations, while the average annual sediment yield value of 1567 $t\cdot km^{-2}$ falls within the range (and below the mean) of values calculated for the badland regions on the Red Deer River (cf. Campbell, 1992). Given the nature of the majority of the landscape adjacent to the main stream channels in the Palliser Triangle, these average values are probably the most realistic assessment of erosional patterns produced to date. They indicate that most of the land surface contributes essentially no sediment to the through-flowing rivers, and that it is the riparian and valley-side areas that are the dominant sediment-yielding areas in the Palliser Triangle.

Holocene climatic changes and fluvial adjustments

The potential effects of climatic change on river systems is a widely debated and contentious issue in fluvial geomorphology (Bull, 1991). There is little agreement about the way in which streams respond to variations in discharge and accompanying sediment load. This complex system-response, threshold-related problem (Schumm, 1977a) is further exacerbated in the Palliser Triangle where the subhumid to semiarid regional climate produces narrow threshold conditions between aggradation and degradation (Graf, 1988). Although general models of climate-change responses in drainage systems (e.g. Brackenridge, 1980; Knox, 1983; Schumm and Brackenridge, 1987) have been widely used to interpret past changes in fluvial systems, they appear to be of limited value as geomorphological-response forecasting tools.

Table 6. Gross and effective drainage areas within the Palliser Triangle calculated from Prairie Farm Rehabilitation Administration (1991; rounded to nearest square kilometre).

River	Contributing region	Gross area (km^2)	Effective area (km^2)	% effective of gross area
South Saskatchewan River drainage basin				
Red Deer	Drumheller to Bindloss	19 849	11 406	57.4
Bow	Bassano Dam to confluence with South Saskatchewan	5023	1403	27.9
Oldman	Lethbridge to confluence with South Saskatchewan	10 499	5549	52.8
South Saskatchewan	Bow-Oldman confluence to Medicine Hat	3558	1280	35.9
	Medicine Hat to Highway 41	9608	4523	47.0
	Highway 41 + Bindloss (Red Deer River) to Lemsford	18 363	6382	34.7
	Lemsford to Gardiner Dam	16 228	6809	41.9
		83 128	37 352	mean 44.9
Milk River drainage basin				
Milk River (Alberta)	North Milk River at International Boundary and Milk River at Western Crossing to Milk River townsite	1436	1282	89.2
	Milk River townsite to Writing-on-Stone Park	1669	962	57.6
	Writing-on-Stone Park to Pendant D'Oreille	1650	1436	87.0
	Pendant D'Oreille to Eastern Crossing	452	423	93.6
		5207	4103	mean 78.8
Milk River drainage basin				
Tributaries (Saskatchewan)	Lodge Creek to International Boundary	1970	1720	87.3
	Battle Creek to International Boundary	2583	1605	62.1
	Frenchman River to International Boundary	5514	4628	83.9
		10 067	7953	mean 79.0
Swift Current Creek drainage basin				
Swift Current Creek	upstream of Rock Creek	1427	1086	76.1
	Rock Creek to Swift Current	1856	1280	68.9
	Swift Current to Leinan	442	229	51.8
	Leinan to Lake Diefenbaker	186	47	25.2
		3911	2642	mean 67.5
Old Wives Lake drainage basin				
(interior basin drainage)	Notukeu Creek to Gravelbourg	4239	3269	77.1
	Pinto Creek to Woodrow	1867	1623	86.9
	Wood River to Gravelbourg	5613	3919	69.8
		11 719	8811	75.2
Total		114 032	60 861	mean 53.4

Table 7. Progressive, downstream, suspended-sediment load increases for main drainage systems in the Palliser Triangle and comparison of contributing, areas and specific sediment yields using approaches of Prairie Farm Rehabilitation Administration (1991) and channel-length analysis proposed in this study.

	From Table 4	Areas as calculated by PFRA (1991)		Areas as proposed in this study	
RIVER / stations	Load increase (x 10^6 t)	Contributing effective area[1] (km^2)	Specific sediment yield (tonnes/km^2)	Contributing effective area[2] (km^2)	Specific sediment yield (t/km^2)
RED DEER					
Drumheller - Bindloss	1.43	11 406	125.37	533	2685.24
***BOW + OLDMAN**					
Bassano+Lethbridge - Medicine Hat	1.24	15 522	79.89	973	1274.75
SOUTH SASKATCHEWAN					
Medicine Hat - Highway 41	-0.10	4523	N/A	322	N/A
SOUTH SASKATCHEWAN +RED DEER					
Bindloss+Highway 41 - Lemsford	1.23	6382	192.73	321	3834.16
MILK					
North Milk River - Milk River town	0.029	1282	22.62	200	144.96
MILK					
Milk River town - Eastern Crossing	0.256	2821	90.75	253	1012.18
SWIFT CURRENT CREEK					
Leinan - Lake Deifenbaker	0.061	47	1297.87	42	1458.63
TOTAL	4.146	34 693	119.51	2645	1567.49

[1] area that contributes runoff to main channels for a flood with a two-year return period
[2] calculated as channel length x 2 km
N/A - Not applicable; load shows minor decrease between Medicine Hat and Highway 41 stations.
* The South Saskatchewan drainage system upstream of Medicine Hat.

The response of rivers to factors external to the fluvial system should be manifest in coherent regional patterns, particularly stream profiles. There has been very little analysis of this type conducted in the Palliser Triangle; however, studies in central and southern Alberta demonstrate an important common pattern (e.g. Bryan et al., 1987; Rains and Welch, 1988; Campbell and Evans, 1990; Campbell et al., 1993; O'Hara and Campbell, 1993; Rains et al., 1994; Barling, 1995). Numerous tributaries to the Red Deer and North Saskatchewan rivers (north of the Palliser Triangle) show strong down-valley convexities in their profiles just above their main stream entry points. This pattern has been interpreted as resulting from the tributaries being unable to incise as rapidly as the main stream. As a result, terrace formation along tributary streams lagged millennia behind that of the through-flowing rivers, indicating that the two systems were out of phase (Rains and Welch, 1988). It remains to be demonstrated if this pattern characterizes the Palliser Triangle as a whole.

Establishing correlations between past variations in fluvial processes and paleoclimatic regimes in the Palliser Triangle is restricted by the scattered locations of dated fluvial deposits (O'Hara and Campbell, 1993; Rains et al., 1994) and the lack of high-resolution proxy climate records. The best paleoclimatic records available from the region (Chappice Lake (Vance et al., 1992, 1993) and Harris Lake (Sauchyn, 1990; Sauchyn and Sauchyn, 1991; see "Climate, Vegetation, and Soils") cover only slightly more than 50% of the time since regional deglaciation (cf. Klassen, 1994). The nature of fluvial responses to the broad climatic intervals recognized in the Chappice and Harris Lake records (Hypsithermal, Neoglacial, Medieval Warm Period, and Little Ice Age) are speculative at best.

Initial postglacial stream incision appears to have been primarily in response to glacioisostatic rebound, augmented by large volumes of meltwater from the Laurentide Ice Sheet and the re-established mountain-fed rivers. However, it is possible that streams also reflect accelerated erosion under relatively wet climatic conditions. An absence of dated terrace deposits along tributaries of the Red Deer River (Campbell and Evans, 1990; Campbell et al., 1993; Rains et al., 1994) suggests a marked reduction in the rate of tributary valley incisions between ca. 7000 and 3000 BP. Bryan et al. (1987) proposed that the onset of more arid conditions at ca. 5.5 - 4.5 ka BP, as evidenced by extensive loess deposition, led to a significant reduction in the rate of channel incision. This interval corresponds with a low lake-level stand at Chappice Lake (Vance et al., 1992, 1993), near the termination of an extended period of more arid conditions registered at Harris Lake (Sauchyn, 1990; Sauchyn and Sauchyn, 1991; Last and Sauchyn, 1993).

Extensive terrace deposits dated from ca. 2.5 - 2.8 ka BP occur along tributaries of the lower Red Deer River (Campbell et al., 1993; Rains et al., 1994). Below this major terrace, sequences of terrace deposits and channel fills date between about 1.5 ka BP (Campbell and Evans, 1990) and the last few hundred years (O'Hara and Campbell, 1993). This alternating incision and filling sequence encompasses a late Holocene trend towards a moister climate (Sauchyn, 1990; Sauchyn and Sauchyn, 1991; Last and Sauchyn, 1993), culminating in Little Ice Age, as recognized in the Chappice Lake record (Vance et al., 1992, 1993).

Interpretation of sediment sequences and terraces as records of fluvial responses to climatic variations may be both highly plausible and grossly misleading. The complex interrelationships between stream responses and climatic variations preclude simple correlations (O'Hara and Campbell, 1993). Rains et al. (1994) conclude that terrace sequences in this region show overlapping aggradational and degradational phases, with few indications that terrace formation in different stream systems is synchronous. In the absence of additional research across the Palliser Triangle, and detailed alluvial chronologies that demonstrate a coherent, synchronous regional response of fluvial systems to past climatic variability, it would be premature to conclude that responses to future climate change can be predicted with any degree of confidence.

MASS WASTING PROCESSES

David J. Sauchyn

Introduction

The mass wasting of soil and rock involves a variety of processes. As a result, an extensive terminology has been developed that is often used indiscriminately. The most widely adopted classification of mass wasting processes is based on "type of movement primarily and type of material secondarily" (Varnes, 1978, p. 11). Five principal types of movement are recognized: falls, topples, slides, lateral spreads, and flows; and two types of materials: bedrock, and either coarse or fine engineering soil (debris or earth, respectively; Varnes, 1978). Most slope movements are complex, involving a combination of two or more of these processes. Sliding is usually a component of mass wasting, particularly during the initial failure or release of soil and rock. The term 'landslide' has traditionally been used to refer to almost all varieties of mass wasting (Varnes,1978). Thus, whereas sliding technically is only the failure of earth material over a distinct shear plane, the term landslide commonly encompasses other types of slope movement.

Mass wasting is not generally associated with landscapes of low relief and gentle slopes. Thus the perception of the prairie landscape as geomorphologically inert contrasts with the significance of mass wasting as a process of Holocene landscape modification. Landslides are 'ubiquitous' in the major river valleys (Thomson and Morgenstern, 1978, p. 516), along deeply incised tributaries and on the flanks of plateau uplands, notably the Cypress Hills. De Lugt and Campbell (1992) concluded that landslides are of major formative importance in the evolution of the landscape of southern Alberta, and Mollard (1977) considered massive retrogressive failure of Cretaceous clay shale in the Interior Plains to be one of four regional landslide types in Canada (landslides associated with recurring geological, geomorphic, geohydrological, and geotechnical factors).

The geology and geomorphic history of the Palliser Triangle strongly favours mass wasting. Most slopes have developed since regional deglaciation in poorly consolidated surficial materials. The landscapes with highest relief and steepest slopes are plateau uplands and ice-thrust hills, as well as meltwater channels where incision commonly exposed about 100 m of Quaternary sediments and Cretaceous bedrock (Kehew and Lord, 1986). In general, this is a young landscape which continues to adjust to geological events of the late Pleistocene. Soil creep (slow distributed earth flow; Varnes, 1978) is characteristic of treeless rolling to hilly topography, whereas shallow flows, slides, and falls of weathered rock occur frequently on steep unvegetated slopes (de Lugt and Campbell, 1992). However, these low-magnitude quasi-continuous processes have little impact on human activities in this sparsely populated region and thus are scarcely documented.

Landslides, on the other hand, are the subject of a large body of literature in engineering geology, principally because they seriously constrain the construction and maintenance of dams and valley crossings. Much of this literature focuses on the geology and mechanics of individual historical slope failures rather than providing a regional perspective (e.g. Yoshida and Krahn, 1985; Sauer and Christiansen, 1987; Cruden, et al., 1993). Slope stability in the Cretaceous bedrock of the Interior Plains is understood largely from geotechnical studies; initially those associated with the Gardiner Dam (which created Lake Diefenbaker; Fig. 2), the first major structure in the Palliser Triangle constructed in the shales of the Bearpaw Formation (Mollard, 1952; Peterson, 1954; Terzaghi, 1955). The following summary of the nature and causes of landsliding in the Palliser Triangle is largely based on these studies, supplemented by overviews (Scott and Brooker, 1968; Mollard, 1977; Thomson and Morgenstern, 1977, 1978). This review is followed by a discussion of landsliding from a geomorphological perspective, focusing on the postglacial evolution of meltwater valleys by interacting mass wasting and fluvial processes.

Landsliding processes and morphology

Failure of Cretaceous clay shales in this region has been described as massive retrogressive gravity creep (Terzaghi, 1955). Slow progressive slip, involving residual angles of shearing resistance, occurs along planes of weakness at various elevations, causing bedrock and drift to move towards the valley floor at rates ranging from centimetres to metres (in exceptional cases) per year. Many apparently inactive landslides may be moving at rates too slow to detect without careful monitoring (Sauer, 1975). The ratio of shear strength to shear stress (factor of safety) typically approaches unity for dormant landslides (e.g. Misfeldt et al., 1991). Such landslides are easily reactivated by any process or event that increases the prevailing stress or decreases the frictional resistance to shear.

Strongly differentiated horizontal strata and prior deformation of weak beds favour translational failure. With large gradients in hydraulic conductivity and variations in shear strength, sliding is confined to distinct horizontal beds and slide-mass morphology is dominated by graben structures (Fig. 28A; Mollard, 1977; Thomson and Morgenstern, 1978). Rotational landsliding occurs in more massive bedrock and Pleistocene deposits. Reverse slopes and arcuate subparallel ridges and depressions are diagnostic of rotational movement (Fig. 28B). Commonly, landslides in

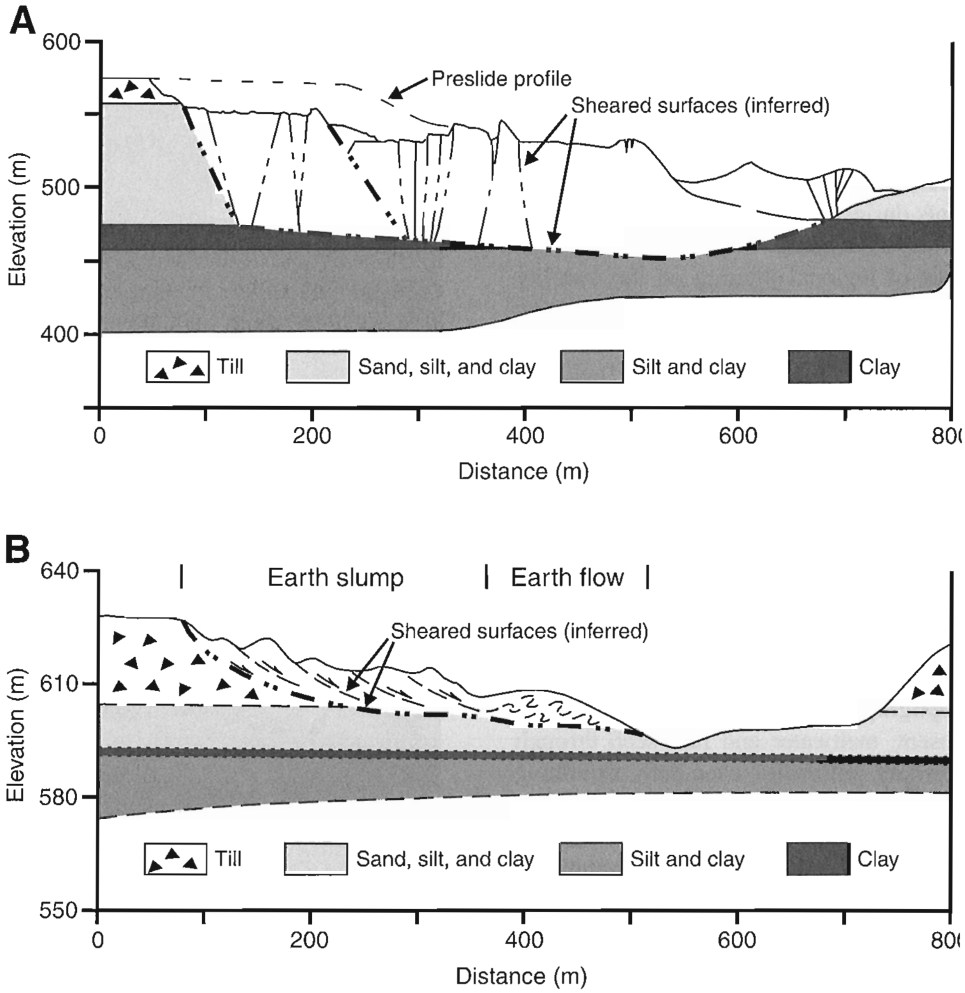


Figure 28. *Types of landslide movement.* ***A)*** *Translational failure: sliding is confined to distinct horizontal beds and slide mass morphology is dominated by graben structures. Favoured where there are strongly differentiated horizontal strata and prior deformation of weak beds. Modified from Cruden et al. (1993) (see also Campbell and Evans, 1990; Misfeldt et al., 1991).* ***B)*** *Rotational failure: characterized by reverse slopes and arcuate subparallel ridges and depressions. Occurs in more massive bedrock and Pleistocene deposits. Modified from Scott and Brooker (1968). Most landslides in the Palliser Triangle are complex and involve several types of movement.*

the Cretaceous shales are complex mass movements. The upper, middle, and distal sections of these landslides are dominated by earth-slump (rotational) flow, earth-block (translational) slide, and earth flow, respectively (cf. Varnes, 1978).

Individual landslides typically extend for several kilometres along valley sides and can cover tens of square kilometres (Fig. 29). As landsliding is retrogressive in space and transgressive in time, an individual slide records several periods of activity. The width of failure perpendicular to the sides of meltwater channels is influenced by the degree of bedrock deformation resulting from catastrophic incision of the valley (Matheson and Thomson, 1973) and by transverse tension cracks that promote retrogressive failure of similar-sized wedges of bedrock and drift. These cracks ('fracture traces' of Scott and Brooker, 1968, p. 35) develop on the upland, parallel to the valley edge during incipient failure of the adjacent valley side, and may correspond to regional joints where valley orientation follows the strike of a joint set. Commonly, the orthogonal fracture pattern in the Cretaceous bedrock was propagated upward into Quaternary sediments during glacial unloading and associated isostatic rebound (Babcock, 1973, 1974; Mollard, 1988). The influence of regional jointing on the stability and morphology of valley sides may be particularly strong in areas of thin to discontinuous Quaternary sediments, where postglacial erosion has exposed the fractured bedrock to subaerial erosion. De Lugt and Campbell (1992) suggested that the rectangular pattern of coulees in southern Alberta is an expression of the regional joint system.

The preceding descriptions characterize the majority of landslides in the Palliser Triangle; those that occur in marine shale (principally the Bearpaw formation, see "Geologic Setting"). However, a second major class of landslides are those associated with plateau uplands, particularly the Cypress Hills (Fig. 2), owing to their distinctive geological and topographic setting. With Pleistocene deposits thin or absent, meltwater and rain seep through loess and coarse Tertiary sediments, eventually saturating the underlying Cretaceous shales. In the western Cypress Hills, the combination of steep slopes (with local relief of >200 m), Tertiary caprock, and 100 mm more precipitation than occurs on the surrounding plains, promotes deep-seated rotational landsliding (Sauchyn, 1993). One of the larger (>1.5 Mm^3) historic landslides in the Palliser Triangle occurred in the western Cypress Hills at Police Point, along upper Battle Creek valley (Fig. 30). Tension fractures and a headward scarp began to form in the early 1960s, but most of the slope failure occurred in May 1967, after 1.5 m of snow fell and melted within a few days (Janz and Treffry, 1968). Assuming that the processes responsible for the Police Point landslide are typical for the area, landslides in the Cypress Hills are likely more catastrophic than elsewhere in the Palliser Triangle.

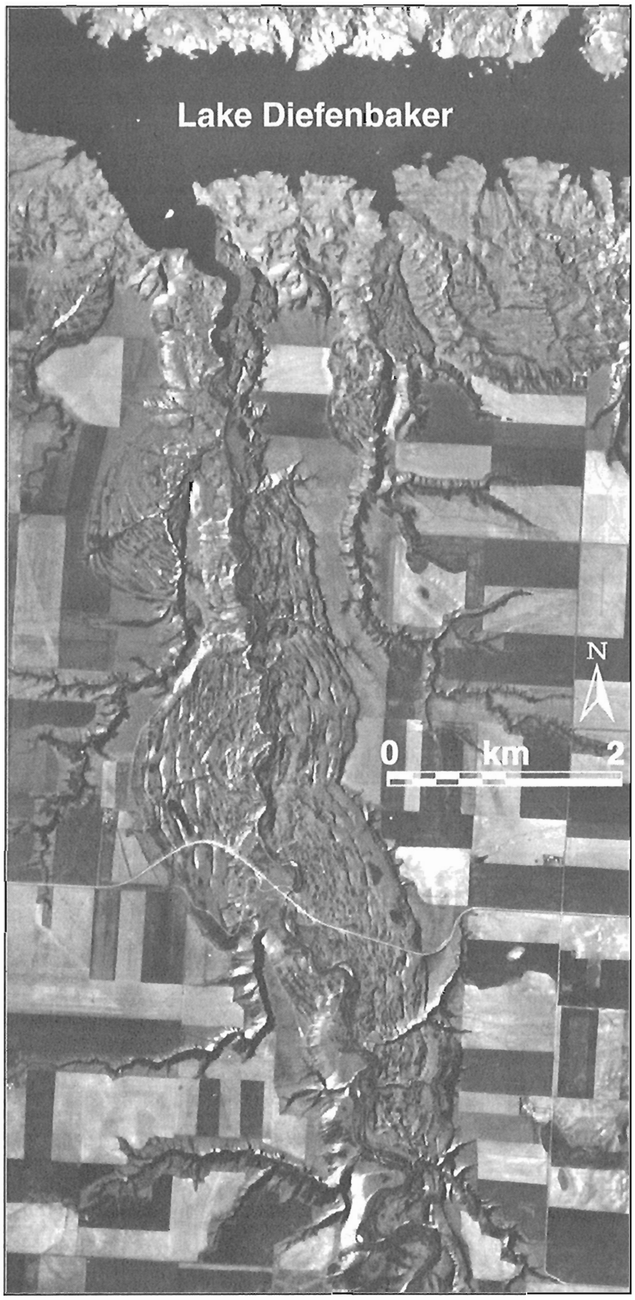


Figure 29. *Vertical air photograph of lower Swift Current Creek valley. Slopes in Quaternary sediments are stable, as evidenced by the morphology of the tributary valleys. In the shale, however, massive rotational landslides have occurred with the reduction in confining pressure. Similar massive retrogressive slope failure characterizes the nearby South Saskatchewan River valley (visible at top of photo). NAPL A21739-38.*

In addition to landslides in Cretaceous shales and those associated with plateau uplands, a third, relatively minor, class of landslides in the Palliser Triangle are those confined to Quaternary sediments. These are generally shallow and rotational, and most commonly occur in till and glaciolacustrine sediments that have been incised during deglaciation, or because of Holocene fluvial activity.

Causes of landsliding

Although landslides in the Palliser Triangle can be divided into three classes on the basis of stratigraphy and morphology, they are caused by a few common factors. The overriding cause of landsliding in the region (and the Interior Plains generally) is the inherently low shear strength of the poorly indurated Upper Cretaceous shales, especially those that contain bentonite, and the deposits derived from them (Scott and Brooker, 1968). According to Mollard (1977) and Thomson and Morgenstern (1977, 1978), specific geological and geomorphic factors contributing to slope failure are i) over-consolidation of the Cretaceous clay; ii) local deformation from ice thrusting and rebound of strata under incising valleys; iii) rapid downcutting of deep channels by glacial meltwater and postglacial streams; iv) regional fracturing of bedrock and Quaternary sediments; v) distribution of groundwater; and vi) lateral shifting of stream channels.

Some of these conditions or events contribute to increased stress; most cause decreased resistance to shear. They can be classified as transient (quasi-continuous), active (episodic), or passive (Crozier, 1986). Geomorphic, hydrological, or anthropogenic processes may be either transient or active factors that can trigger landsliding, while passive factors include the inherent geological and engineering properties of the bedrock (such as the many and abrupt vertical and lateral changes in facies). Lithologically, the unstable units are marine, argillaceous, and bentonitic. The clay component of these sediments has high plasticity, especially where bentonite (predominantly montmorillonite) is present as an admixture or in pure thin seams.

Structurally, the beds of lowest strength are preconsolidated, sheared, and poorly indurated. Although the weight of overlying sediments has not significantly indurated the Cretaceous shales, the depth and duration of loading was sufficient to produce structural changes prior to erosion of more than 900 m of sediment from the Interior Plains, primarily during the late Tertiary (Nurkowski, 1984). Slow expansion of the unloaded clay, at an exponentially decreasing rate, produced joints, slickensides, void space, and increased water contents. This softening of the clays was universal and decreased with depth. Clay beds were further altered by glacial isostatic rebound and more rapid local changes in stress produced by ice-thrusting and the

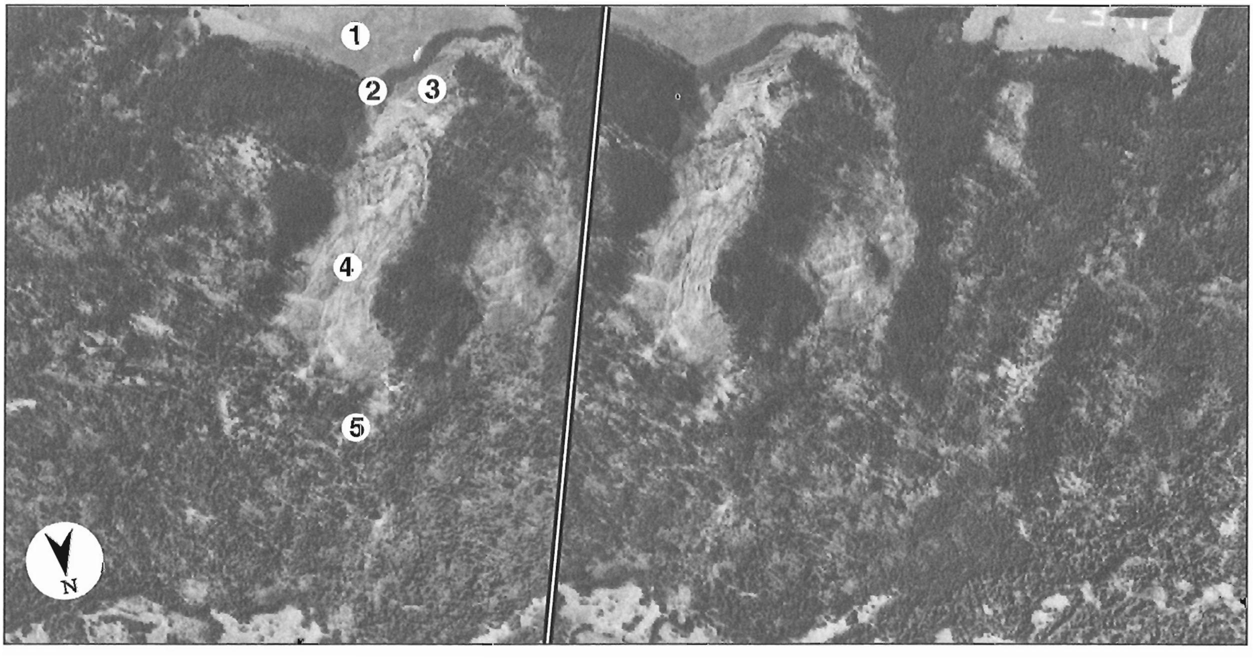


Figure 30. *Stereo-pair of Police Point landslide, south side of Battle Creek in the West Block of the Cypress Hills.* ***1)*** *upper plateau surface;* ***2)*** *upper scarp exposing Cypress Hills Formation;* ***3)*** *rotated slump blocks;* ***4)*** *gully erosion within Cretaceous bedrock; and* ***5)*** *sediment washed from landslide into the forest. Bottom of landslide lies about 140 m below plateau surface. Airphotos AFL W AS2343-249, 250. Modified from Sauchyn and Lemmen (1996).*

downcutting of meltwater channels. Shearing, brecciation, slickensides, and faulting reduced shearing resistance to near residual angles. Valleys sides in ice-thrusted terrain present unique geotechnical problems, especially where surface expression of glacial tectonism is lacking (Sauer, 1978; Stauffer, et al., 1990).

Meltwater erosion rapidly removed a considerable load from the strata underlying valley walls and floors. The flexure of these strata is expressed as raised valley rims, and as gentle anticlinal structures under the valley floors (Matheson and Thomson, 1973). Elastic rebound of the argillaceous bedrock is typically 1-3 m, but may have been as much as 10% of valley depth (Matheson and Thomson, 1973). The degree of deformation depended on the rate of meltwater erosion and previous rock-stress history. In the western part of the Palliser Triangle, where a greater thickness of Paleocene sediments were deposited, the Cretaceous rocks may have been more indurated and therefore less subject to deformation and slip during valley cutting. For example, there is less landsliding in the St. Mary River valley of south-central Alberta than in other large valleys in the Palliser Triangle (Scott and Brooker, 1968).

The vast majority of landslides in the southern Interior Plains occur in the Bearpaw Formation, which has well documented engineering properties (Terzaghi, 1955; Scott and Brooker, 1968; Mollard, 1977). More than 300 m of Bearpaw marine shale underlie surficial deposits throughout much of the Palliser Triangle. An upper zone that has been disturbed and softened by weathering and swelling has high natural moisture contents and low shear strength. Liquid limits (moisture content at which fine sediment behaves as a viscous fluid) average 65-100%, while plasticity indices (the difference between liquid and plastic limits, high values indicate very plastic sediment) average 40-80% (Scott and Brooker, 1968). At the Gardiner Dam site, liquid limits averaged 115%, with a maximum liquid limit of 265% for bentonitic clay, while plasticity indices averaged 92% (Mollard, 1977). Slopes as low as 4° failed during construction of the dam. This prompted a re-evaluation of laboratory shear-strength parameters: cohesion of 40 $\mathrm{kN{\cdot}m^2}$ and a 20° angle of shearing resistance. Field measurements on the failed clay revealed zero cohesion and 9° of frictional resistance (Mollard, 1977).

Historic landslides have been triggered by lateral stream-channel migration or by groundwater recharge and positive porewater pressure related to wet cool years, major rainfalls, and melting of deep snowpacks (Thomson and Morgenstern, 1978; Sauchyn and Lemmen, 1996). Thomson and Morgenstern (1977, p. 522) regarded the effects of climate on landsliding to be minor compared to geological and engineering factors, given the "overwhelming influence of bedrock type". However, bedrock type is a passive factor and hence does not trigger landslides. Rather, it is the transient and active geomorphic and hydroclimatic conditions that serve as triggering factors. Beaty (1972a), Barendregt and Ongley (1979), and de Lugt and Campbell (1992) documented aspect control on landsliding in southern Alberta. There is a significantly greater incidence of larger slides on north- to east-facing slopes, where rates of evapotranspiration are lower and drifted snow accumulates, leading to locally high water tables.

Slope instability is associated with high or perched water tables, nonhomogeneous groundwater pressure, and increased pressure gradients from rapid drawdown of groundwater during recession of flood water or rapid valley incision. In addition to the effects of high porewater pressure, shear strength is also reduced by dissolution of salts in the marine strata and deflocculation of clays. Human activities causing slope failure include excavations, but usually involve the use of water, in particular reservoirs (Thomson and Morgenstern, 1977), and irrigation (Beaty, 1972b; Campbell and Evans, 1990). Extensive irrigation in southern Alberta has locally elevated groundwater levels. Irrigation return flow recharges groundwater and creates flow in stream channels that otherwise would be intermittent and much less capable of undermining adjacent slopes.

Numerous geotechnical studies of the Cretaceous bedrock outline the mechanics and passive factors causing landsliding, but such studies tend to have limited temporal and spatial perspectives. For example, as river-channel shifting occurs relatively slowly from an engineering perspective, the stage of valley evolution may or may not be considered an important factor affecting slope stability at a project site. The objective of the following discussion is to consider landsliding as a component of the valley geomorphic system; a process of postglacial landscape evolution.

Valley hydrology and geomorphology

Given the tectonic stability of the Interior Plains, the major valleys (commonly imposed on Tertiary drainage systems by meltwater erosion) have evolved since deglaciation through the interaction of hydrological, fluvial, and slope processes. Landsliding is the dominant process responsible for widening the tops of valleys and reducing slope angles. Christiansen and Sauer (1988) estimated that the Frenchman River valley is 80 m less deep and almost three times wider than the original meltwater channel, with the basal valley fill largely composed of landslide debris. Landsliding propagates up tributary valleys as they expand headward and incise to a critical depth. De Lugt and Campbell (1992) observed that relatively small mass movements occur frequently as coulees extend into the prairie surface, while at the mouths of the coulees, landslides expand retrogressively, becoming larger and more stable.

Drainage adjacent to major valleys can be captured by tension fractures or diverted by raised valley rims. Tributary streams may flow parallel to a mainstem river a short distance before the confluence, or surface water may collect behind raised rims and seep through tension fractures into clay-rich strata. Seeping groundwater is refracted at vertical changes in facies, with accelerated flow through joints and sandy beds contrasting the extremely low permeability of the clays. In badlands, pipes form along fracture systems and play an important role in generating mass movements, which commonly expose large piping shafts (Barendregt and Ongley, 1977; Campbell, 1989). Preglacial valleys infilled with sand and gravel act as drains, depressing water tables. The conspicuous absence of landsliding is often the only surface expression of such infilled valleys. Tributary valleys also depress water tables and can inhibit landsliding in adjacent sections of the main valley, although landslides can be numerous in tributary valleys where water tables tend to remain high.

Meandering of rivers and deflection of flow against valley sides by stable mid-channel bars are major active triggers of landslides. Thomson and Morgenstern (1977) found a high correlation between stream sinuosity and basal erosion of valley sides. Along the rivers they examined in southern Alberta (the Red Deer, Bow, South Saskatchewan, and Oldman), 90% of landslides occurred at meander bends. Landsliding is less common where terraces occur along the same rivers. Terraces serve to reduce the overall valley-side slope, provide a natural toe load, and may overlie presheared beds, suppressing their influence on slope stability. In contrast to these major through-flowing rivers that head at glaciers and snowfields in the Rocky Mountains, underfit streams that head on the plains and occupy meltwater channels have considerably less flow, and are far less likely to trigger landslides by basal erosion of valley sides. Nonetheless landsliding is also ubiquitous along these valleys. A useful study would be to compare landslides along such meltwater channels with those bordering through-flowing rivers (cf. Sauchyn and Lemmen, 1996).

The low residual strength and fine texture of the Cretaceous bedrock results in prolonged erosion and instability of new landslides, inhibiting colonization of plants for years or decades. Landslide scarps and deposits are therefore significant sources of sediment to the fluvial system, and may be virtually the only sources on otherwise well vegetated slopes. Sediment-laden runoff from hillslopes can alter local stream geometry and water quality, producing downstream impacts that often represent more significant hazards than the direct effects of landslides (Sauchyn and Lemmen, 1996). Where failure surfaces extend to or beneath a valley floor, drainage is impounded or diverted (Cruden et al., 1993). Channel incision of landslide dams involves significant local adjustments of the longitudinal profile and plan geometry of streams that may require millennia to equilibrate (Sauchyn and Lemmen, 1996). Thus the significance of landsliding in valley evolution is a function of the length of the reaction and relaxation times (Brunsden and Thornes, 1979) of the fluvial system relative to the frequency of major landslides.

Timing of postglacial landsliding

The frequency of landsliding is related to the timing of active and transient hydroclimatic, glaciofluvial, and fluvial geomorphic events. Even though landslides are ubiquitous in the Palliser Triangle, ages are known for only a few. Thus we are unable to adequately test hypotheses concerning the relative significance of controls on the tempo of landsliding: valley incision, climatic change, extreme hydroclimatic events, and overall valley evolution (reduction in slope angles). A major episode of immediate postglacial landsliding is assumed from the depth and rapidity of valley incision by glacial meltwater. In most instances, the only evidence to support this assumption is the subdued landslide morphology. One of the few sites with good chronological control is in the Frenchman River valley, where fluvial sediment dated ca. 11.5 ka BP overlies significant landslide debris (Christiansen and Sauer, 1988). Of the landslides surveyed by Thomson and Morgenstern (1977, p. 522), nearly 80% are inactive and appear very old, suggesting that "landsliding must have occurred on an enormous scale" with the initial downcutting of the postglacial valleys.

Chronological evidence of late Holocene landsliding is available from the plains (e.g. Campbell and Evans, 1990), however, the majority of dated landslides in the Palliser Triangle are from the Cypress Hills (Goulden and Sauchyn, 1986; Sauchyn, 1993; Sauchyn and Lemmen, 1996). Absolute and/or relative ages have been determined for 21 landslides in this region and all are less than ca. 5100 BP (Fig. 31). Stratigraphic evidence from Elkwater and Harris lakes (Fig. 2) suggests that landsliding dramatically affected the sediment budgets of these lakes around 5100 BP (Vance and Last, 1994) and 4000 BP (Last and Sauchyn, 1993), respectively. Maximum landslide ages of ca. 1775 BP (Sauchyn and Goulden, 1988), 2240 BP and 2410 BP (Sauchyn and Lemmen, 1996) were obtained from material underlying landslide debris at three sites in the Cypress Hills. Minimum dates are available for three other sites (for details see Sauchyn and Lemmen, 1996). It must be emphasized that since landslide movement is progressive, with multiple phases of activity, these dates simply document the most recent period of slope movement. Nonetheless, the data demonstrate that most landslides in the western Cypress Hills have been active during the late Holocene.

Although the limited chronological data do not negate the possibility that landsliding has been an essentially continuous process through the Holocene, consideration should be directed to the transient and active processes that may have triggered or reactivated landslides during the late Holocene. Furthermore, analysis of relative age data suggests clustering of landsliding events in the late Holocene, rather than random occurrences (Fig. 31; Goulden and Sauchyn, 1986). Climate, as a control of the regional groundwater table, has been suggested as one factor that influences landslide activity in the Cypress Hills region (Goulden and Sauchyn, 1986; Sauchyn, 1993; Sauchyn and Lemmen, 1996). During the early and middle Holocene, the climate was generally both warmer and drier than at present and regional water tables were markedly lower (Vance et al., 1995), resulting in an extensive period of surface erosion under dry conditions. A change to wetter and cooler climate after ca. 4 ka BP raised regional water tables (as reflected by lake-level changes, Vance et al. 1995), prompting a period of slope readjustment (Sauchyn, 1990). With rising water tables, clay-rich strata at progressively higher elevations are subject to excess porewater and lowered resistance to shear. This increases the potential for sliding at multiple depths, as well as below valley slopes that were stable under earlier climatic conditions. Superimposed upon these long-term, climatically controlled changes in water tables is the annual cycle of seasonal variations in hillslope and spring activity. Hence water-table level represents a transient factor which influences geomorphic response to active factors, such as stream channel shifts and extreme hydroclimatic events.

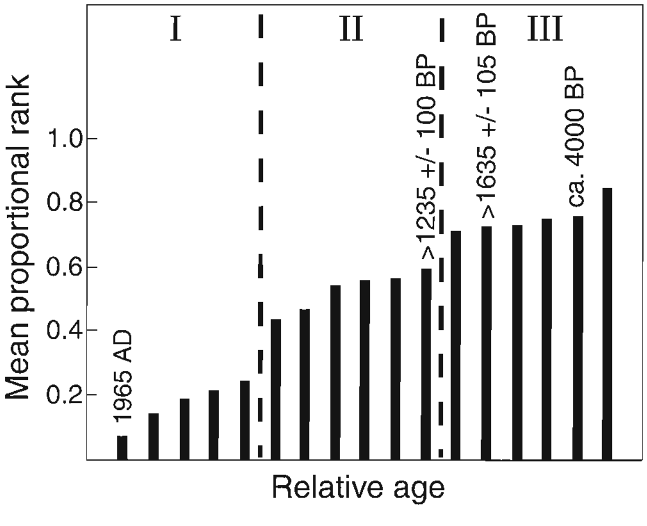


Figure 31. *Relative ages of 17 landslides in the western Cypress Hills with corresponding absolute ages where available. Mean proportional rank refers to an index of relative age indicators; I, II, and III are distinct groups of landslides identified by cluster analysis (for details* <u>*see*</u> *Goulden and Sauchyn 1986). Complete data on absolute dates are presented in Sauchyn and Lemmen (1996).*

Given the coarse resolution of available paleoclimatic records, and poor dating control of landslide chronologies, correlating changes in climate and slope stability remains speculative, at best. However, a change towards a wetter climatic regime and associated rising water tables would serve to increase the impact of extreme events (e.g. heavy rainfall, rapid snowmelt) that could trigger or reactivate landslides. It needs to be emphasized that this proposed relationship between climate and landsliding is based on observations from the Cypress Hills, and in the absence of additional studies cannot be confidently extrapolated to settings more typical of the Palliser Triangle (Sauchyn and Lemmen, 1996).

SOIL REDISTRIBUTION

D.J. Pennock

Introduction

Human activity has resulted in an acceleration of the rate of erosion throughout the agricultural region of the Canadian prairies. It is these rates, and the associated redistribution of soil, resulting from recent agricultural activities in the Palliser Triangle (rather than those associated with the full range of Holocene conditions) that are the focus of this review. Recent research has tended to focus on soil redistribution within a landscape rather than on soil erosion alone; erosion connotes loss from a point, whereas redistribution focuses on the transfer of sediment within a landscape and the net losses or gains for the landscape as a whole.

Modelling of wind and water erosion processes has been a major focus of researchers both in geomorphology and in the agricultural sciences. The current generation of process-based models of wind and water erosion (reviewed in Lal, 1994) focus on the three stages common to both types of erosion: i) detachment of soil from the soil matrix; ii) transport of the detached sediment; and iii) deposition of the sediment at some distance away from the source. In water erosion, the principal agents of detachment are raindrop splash and flowing water, either singly or in interaction. In wind erosion, the initial detachment occurs due to the shear stress imposed by the wind itself, but subsequent detachment is caused by the bombardment of the surface by soil particles in transport. Where water is the major agent of transport, flow may occur either as unconfined surface sheets (sheet flow or inter-rill erosion) or in small channels (rill and gully erosion). Where wind is the transport mechanism, particles can be transported by saltation, by surface creep, or as suspended load within the air.

In addition to wind and water, a third source of soil redistribution in agricultural landscapes is tillage. Recent research by both soil scientists (Lobb et al., 1995) and experimental geomorphologists (Govers et al., 1994) has emphasized the importance of tillage redistribution, especially on landscape segments which are convex in both plan (across-slope) and profile (down-slope) curvature. Lobb et al.'s (1995) research in Ontario found average rates of loss of 54 $t{\cdot}ha^{-1}{\cdot}a^{-1}$ from these landscape segments, while Govers et al.'s (1994) research in the Netherlands observed erosion rates of 10 to 40 $t{\cdot}ha^{-1}{\cdot}a^{-1}$. Although comparable research has not been carried out in the Palliser Triangle, the contribution of tillage to overall soil redistribution may be considerable.

Deposition of sediment has received much less attention from process-based researchers, but the use of the radioactive tracer cesium-137 over the last decade in sediment-redistribution studies has greatly expanded our understanding of the patterns of soil redeposition. As will be shown, applications of this technique in Saskatchewan and elsewhere indicate that the great majority of sediment is normally deposited within the confines of the study landscape itself, rather than being exported out of the landscape.

Controls

The primary controls on the rates of soil redistribution can be grouped into four major headings: climatic, vegetation/landuse, soil, and landform controls. The former two show the greatest sensitivity to changes in the climate, whereas the latter two are only indirectly related to climatic controls. Soil and landform factors are of relevance, however, in the development of regional-scale models of soil susceptibility to erosion under both current and projected climatic regimes.

Climatic and vegetation/landuse factors

Both wind and water erosion processes are closely related to extreme (under the current climatic regime) climatic events. Drought conditions are the necessary precursor to widespread wind erosion. Analysis of drought incidence and severity is gravely complicated by the high spatial and temporal variability associated with climatic events on the Prairies (Jones, 1991), with localized droughts recorded in even the wettest of years on a regional basis. In the period from 1929 to 1991, prolonged periods of drought were widespread in the Palliser Triangle in 1933, 1936-1938, 1961, 1968, 1977-1978, 1980-1981, 1984, and 1988 (Jones, 1991). The droughts of 1968, 1977-1978, and 1980-1981 did not occur at times of great consequence to the crop cycle, and widespread wind erosion did not occur; however significant regional-scale wind erosion events were associated with the other drought periods (Jones, 1991).

Water erosion events are closely associated with two types of hydrological events: snowmelt in the spring, and high-intensity rainfall events throughout the snow-free period. In both cases the infiltration capacity of the soil is exceeded and sufficient runoff to detach and transport soil is generated. In the only plot-based studies of erosion on agricultural land in the Palliser Triangle, Nicholaichuk and Read (1978) measured erosion rates from snowmelt runoff which averaged 0.55 $t{\cdot}ha^{-1}{\cdot}a^{-1}$ from summerfallow fields and 0.11 $t{\cdot}ha^{-1}{\cdot}a^{-1}$ from wheat stubble fields over the course of a six-year study. Although the rates are low compared with the other erosion studies discussed below, snowmelt-induced erosion occurs almost every year in the Palliser Triangle.

Studies on the frequency and magnitude of rainfall events required to trigger erosion on agricultural land have not been carried out in the Palliser Triangle. The most commonly used rainfall index is the annual storm rainfall index of the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978). The measure, used by Agriculture Canada to derive Water Erosion Risk Maps (Coote and Padbury, 1988b; Tajek and Coote, 1992), is based on a power function with the two-year-six-hour rainfall amount (in mm) as the precipitation input. Use of this index in Saskatchewan has been criticized as unrepresentative of true prairie conditions (Kachanoski and de Jong, 1985); however, as is often the case with the use of the USLE, no suitable alternative appears to exist. Use of this index in modelling erosion implies that the largest rainfall events are of great consequence in triggering erosion: Kachanoski and de Jong (1985) demonstrated that, on average, 40% of the annual rainfall (R) factor was contributed by the maximum individual storm erosion index in a given year.

The impact of climatic events on soil erosion cannot be separated from the role of vegetative cover on redistribution rates. Fully vegetated surfaces are not susceptible to wind or interill water erosion processes; only the most extreme forms of rill and gully erosion can operate under fully vegetated conditions. Estimates of wind and water erosion rates from fully vegetated pasture or native grassland areas are between 0.001 and 1% of the rates from bare soil (e.g. Evans, 1980; Coote, 1983).

Cultivation of the soil disrupts the natural protection afforded by vegetation. The exposure of the soil surface in the Palliser Triangle is greatly exacerbated by use of tillage summerfallow techniques. Tillage summerfallow is a two-year rotation whereby crops are grown in year one and then in the second year the soil is not seeded to allow recharge of soil moisture stores, as well as mineralization and nutrient release from crop residues. In the second year, weeds are suppressed by successive tillage operations on the soil surface, which leaves the soil surface in a finely divided, dry state - the optimum conditions for wind and, to a lesser degree, water erosion. Protection of the soil is greatly increased if the residue (stubble) from the previous crop is left standing on the field, and recently developed approaches involving minimal tillage or herbicide suppression of weeds in the fallow year have greatly increased the residue cover left on fields in this region.

The major wind-erosion events in the Palliser Triangle are associated with prolonged dry conditions which greatly reduce the amount of vegetative cover on the soil surface from both growing crops and crop residues from previous years. Moss (1935) noted that severe wind erosion was possible in all soil and landform types in the Brown soil zone wherever a succession of crop failures had decreased the residue cover on the soil surface. Crop failures caused by both drought conditions and an assortment of disease and pest problems resulted in massive amounts of wind erosion in the driest years of the 1930s (Hopkins et al., 1946). A major snowmelt or precipitation event following a dry year also has high potential to cause large amounts of soil redistribution.

Soil and landform controls

Climatic and vegetative/landuse controls are clearly paramount in controlling the rates of erosion that occur; however, the response of different landscape types to the same climatic events will vary depending on soil and landform factors.

The most important soil characteristic governing erosion is the aggregation state of the soil, which in turn is a function of particle size and organic-matter content. The size, and stability of the soil aggregates to disruption are evaluated in different ways for wind and water erosion. Water-stable aggregates greater than 0.5 mm (Evans, 1980) and dry aggregates greater than 0.8 mm in diameter, which are intact after dry sieving (Chepil and Woodruff, 1963), are considered to be nonerodible. The size and stability of natural aggregates is controlled by the presence of chemically reactive soil constituents (colloidal-sized clay and organic matter). Sandy and sandy loam soils have limited clay contents and, in the Palliser Triangle, have very low organic matter contents in the range of 1 - 2% (Rostad et al., 1993). Aggregation is poorly developed in these soils and they are very susceptible to wind erosion. Silt- and clay-dominated soils and loamy till soils generally have sufficient clay contents for good aggregation and organic matter contents in the 3 - 4% range (Rostad et al., 1993), and are therefore less susceptible to wind erosion. In any case, however, excessive tillage of the surface can disrupt natural aggregation and make the soil susceptible to erosion. Moss (1935) noted that over-tilled clay soils were the most susceptible to wind erosion throughout Saskatchewan.

The morphology of the land surface is a major control of water erosion. The greater the depth and velocity of the moving water, the greater the erosive stress imposed on the surface. In the original USLE, velocity was related to slope gradient, and concentration (depth) was related to slope length; however, many studies in the past decade have demonstrated that water concentration across-slope is of major importance in most natural landscapes. Attempts have been made to model the influence of across-slope (plan) concentration (e.g., Moore and Burch, 1986) and to incorporate plan curvature into quantitative slope classifications (Martz and de Jong, 1987; Pennock and de Jong, 1987).

Current rates of soil redistribution measured with cesium-137

Technique

By far the most comprehensive record of soil redistribution for the Palliser Triangle and adjacent areas is available from studies over the past decade using the radioactive tracer cesium-137. Cesium-137 (^{137}Cs) was a product of atmospheric nuclear-bomb testing in the 1950s and early 1960s, and deposition of the isotope occurred worldwide (Ritchie and McHenry, 1990). Upon deposition from the atmosphere, the ^{137}Cs isotope was strongly bound to colloids at the soil surface. In the years since its deposition, these colloid-cesium complexes have been redistributed in the landscape by erosion processes. The current concentration of ^{137}Cs at a given sampling station can be measured using gamma spectroscopy. By combining the cesium value with the bulk density of the soil, an area-based cesium concentration in $Bq \cdot m^{-2}$ can be calculated (de Jong et al., 1982, 1983).

The cesium concentrations for each sampling point in a cultivated field can then be compared to the concentrations from an adjacent, uncultivated site and an amount for soil loss or gain for each sampling point in the cultivated field can be calculated. The rates calculated are an integration of the total redistribution occurring in the years since deposition. Normally 1963 (the year when large-scale deposition ceased) is used as the baseline year for calculation of losses or gains.

Since the development of the ^{137}Cs redistribution technique in the mid-1970s, it has become widely used for studies on soil redistribution. A recent literature review (Ritchie and McHenry, 1990) cites over 600 research articles that have used this technique. It has been used in Saskatchewan to estimate soil-redistribution rates since its introduction into Canada by de Jong et al. (1982, 1983) and the specific techniques used are discussed in these references.

Table 8. Soil redistribution values for different landscape types in southern Saskatchewan.

Soil zone	Texture	Net Soil redistribution ($t\cdot ha^{-1}\cdot a^{-1}$)	Mean soil loss ($t\cdot ha^{-1}\cdot a^{-1}$)	% of Stations with loss	Reference
Level and near-level (<2% slope) glaciofluvial and glaciolacustrine landscapes					
Brown	Sandy loam	-16.3 ± 11.6	20.6 ± 8.4	56.7	Pennock and de Jong (1991)
Brown	Silty loam	0.5 ± 7.3	6.0 ± 4.7	43.3	Pennock and de Jong (1991)
Dark Brown	Sandy loam	-35.9 ± 6.4	NA	90.0	Sutherland et al. (1991)
Dark Brown	loam	-38.2 ± 1.6	NA	100.0	Sutherland et al. (1991)
Dark Brown	Silty loam	-3.4 ± 2.6	NA	65.0	Sutherland et al. (1991)
Dark Brown	Silty loam	-6.1 ± 2.8	12.0	60	Sutherland and de Jong (1990)
Level and near-level (<2% slope) till landscapes					
Dark Brown		-8.9 ± 8.3	10.9 ± 7.2	83.3	Pennock and de Jong (1991)
Dark Brown		-8.2±15.4	17.5±10.3	63.9	Pennock and de Jong (1991)
Dark Brown		-8.8±18.3	18.8±12.3	69.4	Pennock and de Jong (1991)
Hummocky and undulating landscapes with 2-5% slopes					
Brown		-5.9 ± 18.2	15.8 ± 10.3	61	Pennock and de Jong (1991)
Dark Brown		-11.0 ± 18.4	19.0 ± 11.7	74	Pennock and de Jong (1991)
Hummocky and undulating landscapes with 6-15% slopes					
Brown		-10.8 ± 25.8	26.4 ± 16.2	63	Pennock and de Jong (1991)
Dark Brown		-13.9 ± 25.2	23.1 ± 12.8	82	Pennock and de Jong (1991)
NA - Values not reported					

Soil redistribution values are reported as tonnes of soil redistributed per hectare per year ($t\cdot ha^{-1}\cdot a^{-1}$). These units can be converted to a more meaningful measure of centimetres of soil lost (or gained) if the bulk density of the soil is known; for example, a soil loss of 10 $t\cdot ha^{-1}\cdot a^{-1}$ occurring on a soil with a bulk density of 1.2 $g\cdot cm^{-3}$ (typical for soils in the Palliser Triangle) translates into a soil loss of 0.83 mm of soil loss per year. Topsoil (or A horizon) thicknesses in cultivated landscapes of the Brown soil zone typically range from about 8 cm thick on knoll positions to 26 cm in footslope positions (Pennock and de Jong, 1990). It has been suggested that the fertility of these soils decreases dramatically once the A horizon thickness drops below 5 cm (Van Kooten et al., 1989). Hence the rates discussed below should be viewed in the context of the time required to reach this 5 cm threshold.

Results

In this summary of results, studies in the Dark Brown soil zone are presented along with those from the Brown soil zone (i.e. Palliser Triangle as defined here). A Saskatchewan-wide study by Pennock and de Jong (1991) indicated that a consistent landscape pattern existed in the two zones. They suggested that a similar set of erosion processes were operative in the two zones and, given the similarities in soil types and agricultural practices throughout the Palliser Triangle, these rates can readily be extended to the region as a whole.

Three summary measures from each study area are used (Table 8):

1. the average value of soil loss or gain for all sampling stations at a given site, termed the net soil redistribution. This represents the net loss (a negative value for net soil redistribution) or net gain (a positive value) for all sampling stations at the site.
2. the mean soil loss associated with only those sampling stations which experienced soil loss; and
3. the relative proportion of sampling stations at the site which experienced soil loss.

The first measure quantifies the net export or gain of soil for the landscape as a whole, while the second and third measures quantify the impact of soil loss within the study landscapes.

The results from level sites (<2% mean slope) in the Brown and Dark Brown soil zones have been divided into glaciolacustrine/glaciofluvial sites and till sites (Table 8). The highest net losses of soil occur at sandy glaciofluvial and glaciolacustrine sites. The proportion of sampling stations within a site that have experienced soil loss, and the mean rate of loss associated with those sites, indicate the severity of erosion within the landscape. In all but one of the nine study areas, the majority of sampling points are losing soil. The extreme cases are two sandy glaciofluvial sites reported by Sutherland et al. (1991), where 90% and 100% of the sampling stations were losing soil.

The results for study areas located in hummocky landscapes have been divided into areas with mean slopes between 2 and 5% and those with mean slopes between 6 and 15% (Table 8). The results are reported as an average of the study areas sampled in each soil zone, as recalculated from the original sources. The net soil losses are highest in the areas dominated by 6-15% slopes. However, none of these losses approach those associated with the level sandy glaciofluvial sites in the Brown and Dark Brown soil zones. The proportion of the hummocky landscape experiencing soil loss is higher and more consistent than that observed for level sites. The 2-5% slope sites have between 61 and 74% of the landscape affected by loss, whereas the values for the 6-15% slope sites range from 63 to 82%. The mean soil losses associated with these sites are high: in the 6-15% slope class they generally exceed 20 $t\cdot ha^{-1}\cdot a^{-1}$ (i.e. >1.50 $mm\cdot a^{-1}$).

The ^{137}Cs can also be used to examine the relationship between soil redistribution and slope morphology in the study landscapes. A clear and consistent pattern of soil erosion and deposition occurs on hummocky landscapes in the Brown and Dark Brown soil zones (Fig. 32). The highest rates of loss are associated with the divergent shoulder and backslope elements (as defined in Pennock et al., 1987), while deposition is concentrated in the convergent footslope elements (Pennock and de Jong, 1991).

The studies discussed above were concentrated in landscapes with no defined external drainage. The rates of soil redistribution associated with fluvially dissected terrain were assessed at two small catchments (Seymour and Floral basins) in the Dark Brown soil zone near Saskatoon. The areas are currently occupied by small, ephemeral stream systems. The parent material of the soil in the Seymour basin (Martz and de Jong, 1987) is dominantly glaciolacustrine silt, while in the Floral basin (Martz and de Jong, 1991) a discontinuous veneer of loamy and silty glaciolacustrine sediments overlies till. At both sites the average slope is between 2 and 5%, but small areas of slopes up to 20% also occur.

The net soil redistribution at both sites is very close to 0 (a net soil gain of 0.6 $t\cdot ha^{-1}\cdot a^{-1}$ for the Seymour basin and a net soil loss of 1 $t\cdot ha^{-1}\cdot a^{-1}$ for the Floral basin). Again, however, the net soil redistribution losses mask the impact of soil redistribution within the basin itself: at the Floral basin 66% of the sampling stations had lost soil and 58% of the Seymour basin had experienced significant soil loss. At the latter site, deposition was very concentrated and 90% of the total soil gain occurred at two sampling stations.

Martz and de Jong (1987, 1991) also observed a clear relationship between landform characteristics and soil loss and gain. They used a combination of slope morphology and catchment characteristics to delineate distinct landscape positions (Table 9). At both basin sites mentioned

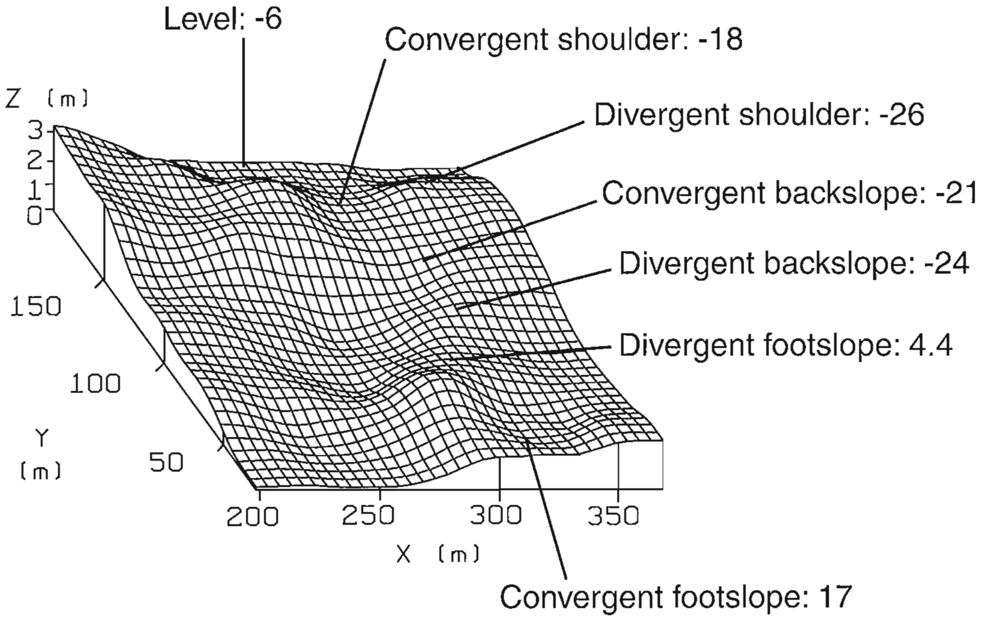


Figure 32. *Generalized landscape-scale model of soil redistribution in the Brown soil zone (original data* in *Pennock and de Jong, 1991). Soil redistribution values are means for that landform element in* $t\cdot ha^{-1}\cdot a^{-1}$*; negative values indicate net erosion. Note that maximum erosion occurs on divergent shoulders; maximum deposition on convergent footslopes. Landform elements are defined in Pennock et al. (1987).*

Table 9. Soil redistribution values ($t \cdot ha^{-1} \cdot a^{-1}$) associated with landform positions in the Seymour (Martz and de Jong, 1987) and Floral (Martz and de Jong, 1991) basins in southern Saskatchewan. Positive values indicate deposition, negative values indicate erosion.

Landform class	Floral basin	Seymour basin
Level	-3.8 ± 12.9	-8.9 ± 14.2
Crest	-2.9 ± 15.5	-9.3 ± 16.0
Midslope	-8.9 ± 15.1	4.0 ± 16.0
Swale	-5.6 ± 12.8	-12.9 ± 12.9
Depression	47.4 ± 45.4	43.6 ± 47.1
Tributary	-26.0 ± 43.7	3.6 ± 34.7
Main channel	not present	216.4 ± 161.3

above, major deposition occurred in the upland depressions. As well, the main channel of the ephemeral stream draining Seymour basin accounts for a high proportion of the deposition in that basin. Tributary features appeared to play different roles at each site, but the level, crest, midslope, and swale features consistently were associated with high levels of loss.

Discussion

Several major insights into soil redistribution in Saskatchewan have emerged from the ^{137}Cs studies. The first is that the on-site impact of soil redistribution greatly exceeds the off-site impact, insofar as the net soil export from the study sites is, for the most part, quite low. Although the majority of sampling stations at each site are experiencing mean soil losses in excess of 10 $t \cdot ha^{-1} \cdot a^{-1}$, most of this sediment is deposited within the confines of the study sites and net export from the sites is low. This suggests that landscape-scale models of soil redistribution must take into account deposition within the field if a realistic sediment budget for a given landscape is to be developed. With respect to the impacts of water erosion, these conclusions are consistent with the analysis of Campbell (see "The Fluvial System"), which indicates that the majority of Palliser Triangle landscape does not contribute significant sediment to the through-flowing fluvial system. However, it also serves to highlight the fact that low rates of net erosion do not reflect the inefficiency of water and wind erosion processes.

At level or near level-sites, the dominant agent of erosion is wind, as the slopes are too gentle for significant water erosion. The dominant controls on the magnitude of soil redistribution at such sites appear to be texture and climate. The highest rates of net soil loss and the highest proportions of affected landscape occur in sandy-textured sites in the drier Brown and Dark Brown soil zones. The variably textured, till-derived soils appear to be more resistant to the effects of wind erosion.

At nonlevel sites, net erosion is a product of wind, water, and tillage processes. Of the nonlevel sites examined, till landscapes appear to have the highest susceptibility to soil loss. Till landscapes in the Black soil zone were also observed to have experienced higher erosion rates (Pennock and de Jong, 1991). This enhanced susceptibility of till landscapes (relative to other parent materials) to erosion is not readily explained using existing erosion models such as the Universal Soil Loss Equation (USLE) .

Despite the differences in absolute rate of soil redistribution in landscapes associated with various parent materials, a clear spatial pattern of soil loss and gain occurs at all nonlevel sites. The highest rates of loss are associated with landform positions that are convex in both plan and profile curvature, yet these shoulder (Pennock et al., 1987) or crest (Martz and de Jong, 1987) units are also where slope length is at a minimum. Clearly the models developed to account for the occurrence of soil erosion in real landscapes have to take account of this distinct pattern of soil erosion observed in these diverse landscape types.

Regional-scale erosion susceptibility estimates

The only regional-scale erosion estimates available for the Palliser Triangle are those developed by Agriculture Canada from application of the USLE and WEE (Wind Erosion Equation) to the soil-polygon data for the Soil Landscape Maps of Saskatchewan and Alberta (Canada Soil Inventory, 1987a,b). The specific versions of the equations used and the parameterization of the equations is presented on the Wind and Water Erosion Risk maps. The use of the small plot-based USLE and WEE equations to estimate erosion susceptibility on the regional and provincial scale is open to criticism from many points of view; however, the maps can serve as a starting point for the development of regional-scale models.

The general trends in erosion susceptibility evident from these maps can be examined in the context of the broad soil groupings of the Palliser Triangle (Fig. 12). The erosion susceptibility of the areas mapped as dominantly Brown Chernozemic (BC) differs depending on soil texture for wind erosion, and the dominant surface slope for water erosion. The dominantly clay, lacustrine landscapes (BC-c) have a negligible water-erosion risk due to low slopes, but are rated as a high risk for wind erosion. The water-erosion risk for both the clay loam till landscapes (BC-cl) and the loamy till landscapes (BC-lm) is closely related to the dominant slope: areas of dominantly 4-9% slopes are rated as a moderate risk, and areas of 9-15% slopes are high risk. The wind erosion risk for these areas ranges from negligible to moderate. The sandy to sandy loam areas of glaciofluvial origin (R-s units) are judged to be of negligible water-erosion risk but severe wind-erosion risk.

The Dark Brown soils (DBC) associated with the Cypress Hills upland differ in erosion risk due to contrasting textures and parent materials. South and west of Swift Current (DBC-lm units) these soils are dominantly formed on loess, and have a high wind-erosion risk and a moderate water-erosion risk. The clay loam, till materials in the western portion of the upland (DBC-cl units) and the area of Black Chernozemic soils on the top of the Plateau (BLC-cl units) have a severe water-erosion risk and a moderate wind-erosion risk.

Two erosion-risk groups are evident in areas mapped as dominantly Solonetzic soils (BS). The northernmost Solonetzic areas (south of Kerrobert, Saskatchewan and southeast of Hanna, Alberta) are dominantly gently sloping, clay to clay loam landscapes and have a negligible water-erosion risk and a low wind-erosion risk. The more rolling, clay loam Solonetzic landscapes south of the Cypress Hills and around Brooks, Alberta have a medium wind-erosion risk and a moderate to high water-erosion risk.

The areas mapped as dominantly Regosolic soils (R) are considered to have severe erosion risk. The area of the Great Sand Hills (R-s) has a severe wind-erosion risk and a negligible water-erosion risk; while the Regosolic soils associated with the river valley and the exposed bedrock (R-var) in southern Saskatchewan have a severe water-erosion risk and a moderate wind-erosion risk.

POTENTIAL EFFECTS OF FUTURE CLIMATE CHANGE ON GEOMORPHIC SYSTEMS

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Introduction

Uncertainties concerning the nature and magnitude of future climate change, as well as the spatial complexity of Palliser Triangle landscapes, makes landuse-scale predictions of geomorphic response to climate at a specific future time untenable (see "Introduction"). The uncertainties do not, however, preclude formulation of meaningful statements on probable impacts by adopting a scenario-consequence approach (cf. Harwell, 1993) to identify a range of possible outcomes for landscape elements that exhibit critical vulnerabilities under specific scenarios. Identification of possible outcomes sets the stage for proactive land management, facilitating rapid adaptation or implementation of mitigation procedures when reliable, long-term regional climatic projections are available, or when trends can be clearly defined through monitoring.

The following discussion provides an overview of probable climatic scenarios for the Palliser Triangle region, as projected by General Circulation Model output. Given the broad perspective of this paper, however, we have chosen to examine four very simple climate scenarios: I) warmer and drier; II) warmer and wetter; III) cooler and wetter; and IV) cooler and drier. Greatest focus will be placed on scenario I, which has been deemed the most probable climatic future for the southern prairie region (e.g. Canadian Climate Program Board, 1995). Analogues for scenarios I and III are contained within the Palliser Triangle paleoenvironmental record. The smallest geomorphic impacts are likely to be associated with scenarios II and IV, as precipitation and temperatures potentially offset each other with respect to the regional water balance.

Many important aspects of climate change cannot be addressed in this preliminary impact assessment. Neither the magnitude of climate change nor the seasonality of these changes, which could be of primary significance, are considered here. Clearly, if an increase in mean annual temperature is manifest primarily in the winter and it results in increased snowpack thickness, increased moisture will be available during the critical spring period, even if mean annual precipitation decreases. Spring moisture promotes vegetation growth (agricultural and otherwise), in turn stimulating a general decrease in erosion rates. In contrast, if warming occurs primarily in summer, it will enhance the already strong moisture deficit, producing drought conditions that will negatively affect vegetation growth, thereby increasing erosion rates.

The frequency of extreme climatic events is not addressed in this assessment either, despite its obvious geomorphic importance. Clearly, a dramatic increase in the incidence of extreme events, whether rainfall or drought, has a considerably greater ability to destabilize landscapes throughout the region, compared to a gradual shift in climatic means.

Finally, the most critical factor influencing regional sustainability, human response, is not included in this assessment. Adaptive responses in terms of agricultural practices and management of marginal lands that are likely to accompany any change in climate will probably be of equal or greater importance to the prairie economy than the climate change itself (Smit, 1991; Stewart, 1991). However, the response of individual farmers and farm operations to gradual climatic change can only be speculative at best, with uncertainties compounded by an inability to predict changes in crop suitability and/or appropriate land-management practices in the absence of reliable long-term regional economic and climate forecasts.

It must be emphasized that the following discussion addresses only issues of geomorphic processes and landscape responses; not the wide range of issues necessary to fully evaluate sustainability. Even in the absence of socio-economic considerations, climatic constraints themselves (e.g. limited moisture availability for crops) will prove to be of greater importance than associated geomorphic responses, at least in the short term. Indeed, in some areas, such as the southernmost extent of Solonetzic soils (Fig. 12), the geomorphic impacts of any climate change are likely to be minimal. However, since these areas are already severely limited in agricultural potential due to inherently poor soil conditions (high sodium concentrations), additional climatic stresses are likely to reduce the amount of cultivated land. Conversely, areas of Regosolic soils (sand dunes, valley slopes) may have high potential for geomorphic response to climate change, but these would have little agricultural impact, since only a very small percentage of such soils are presently cultivated.

General circulation model (GCM) outputs

GCMs are powerful computer-based, three-dimensional representations of the global climate system that have their roots in the numerical modelling methods used to prepare routine weather forecasts in the late 1960s (Environment Canada, 1994). Although the technology and the complexity of these models has developed rapidly over the last three decades, the goal remains the same: to examine responses of the global climate system to altered boundary conditions (i.e. changes in atmospheric composition, incoming solar radiation, albedo, etc.) by simplifying the complex climate system to a series of mathematical expressions. The focus of many recent efforts has been to model the effects of a doubling of preindustrial atmospheric CO_2 concentrations, as ongoing emissions related primarily to fossil fuel consumption are expected to reach this state in the twenty-first century. Recent efforts to couple GCMs with independently developed models of ocean circulation, in addition to incorporating the regional cooling effects of sulphate aerosol emissions, have considerably increased model complexities. This new generation of models has significantly improved simulations of historic climate trends (Wigley, 1995), thereby increasing the confidence with which $2xCO_2$ simulations are viewed. It is these efforts that, in part, contributed to an intergovernmental assessment of climate change conclusion that the balance of evidence suggests that there is a discernable human influence on recent climate (Intergovernmental Panel on Climate Change, 1996).

In spite of this assessment, considerable uncertainties remain concerning the future course of climate change. One of the most significant problems with the GCM simulations of $2xCO_2$ climate is the fact that they are, by definition, global. As a result, regional implications are exceedingly difficult to discern. However, for inland subhumid and semiarid regions in general, and the Palliser Triangle area in particular, several climate-model simulations of an enhanced greenhouse world point to a decrease in summer precipitation accompanied by increased temperature (Karl et al., 1991), raising the spectre of more frequent drought. Results of the Canadian Climate Centres (CCC) 1990 second-generation GCM for a $2xCO_2$ suggest the following for the Palliser Triangle region:

I. mean annual temperature will increase, with greatest increases (5-9°C) occurring in winter, and summer increases in the range of 3.5-6°; and

II. precipitation will show a marked increase in winter and late spring of 5 to more than 40%, and a general decrease in summer of 5-15% (Wheaton et al. 1992)

Additional regional assessment for the same GCM output by Saunders and Bane (1994) arrived at much the same conclusions, estimating that mean annual temperature would increase by 5°C (with the greatest increase occurring in winter), although mean annual precipitation in this study was expected increase in the order of 50-150 mm. The authors qualify these precipitation estimates by pointing out that great spatial variability exists in these projections and that only spring (March-April-May) precipitation increases are significant across the entire prairie region (Saunders and Bane, 1994). Therefore, although great uncertainties remain, the most sophisticated models available for developing long-term projections of climate change suggest that the Palliser Triangle region will be warmer, and likely drier, in a $2xCO_2$ world.

Scenario I – warmer and drier

A future climate warmer and drier than at present would have the greatest impacts on environmental, social, and economic systems in the Palliser Triangle, as it would enhance the already strong negative moisture balance – the greatest constraint on sustainability at present. With respect to geomorphic processes, the greatest impacts are likely to result from indirect responses controlled by vegetation. Heightened aridity and increased drought, producing decreased vegetation cover, would increase potential sediment supply to all geomorphic systems. The mid-Holocene probably serves as the best analogue for this scenario, although similar conditions may have prevailed as recently as the Medieval Warm Period (ca. 900-1200 AD).

Estimates of the length of an extended drought interval required to initiate large-scale mobilization of presently stabilized sand dunes range from about a decade (Wolfe, 1996) to upwards of 25 to 30 years (David, 1971). However, dune size will influence the rate and timing of reactivation. Large dunes, in which moisture is almost entirely dependent on direct recharge by precipitation, would activate more rapidly than smaller dunes, where groundwater may contribute directly to moisture content, thereby stabilizing vegetation cover. Local deflation sites would form on dune surfaces wherever vegetation has died back, leading to the development of blowout depressions. Modelling of sand dune mobility under conditions where drought represented the norm, rather than the extreme, Wolfe (1997) concluded that although dune activity would increase markedly, dunes would retain a parabolic morphology characteristic of semiarid environments (e.g. barchan dunes would not be formed). Extremely rapid reactivation of stabilized sand dunes is only likely through destructive human or animal activity, and could occur under even moderate climatic stresses.

Response of fluvial systems in the Palliser Triangle to climate change in general, and warmer and drier conditions in particular, is especially difficult to evaluate given that the vast majority of water in through-flowing drainages is derived from the Rocky Mountains and foothills, regions where climate change may be manifest differently than on the southern prairies (e.g. Cohen, 1991). In arid and semiarid environments, streams characteristically exhibit nonlinear responses to changes in precipitation (Dahm and Molles, 1985), and increasing temperatures generally associated with marked decreases in runoff (cf. Langbein, 1949). Verhoog (1987) demonstrated that the greatest levels of change in discharge and sediment yields are likely to be seen in areas like the Palliser Triangle, as they are presently transitional between humid and semiarid climates. Yet it is not clear how entire fluvial systems will respond; the trends remain hypothetical (Verhoog, 1987).

Cohen (1991) examined the impact of fifteen climate warming scenarios on runoff in the Saskatchewan River basin. Estimated runoff ranges varied from a 40% increase to 60% decrease, compared to the 1951-1980 mean. The great variability in these estimates relates mainly to uncertainties in GCM capabilities to project precipitation, particularly in the mountains. Modelling by Nkemdirim and Purves (1994) suggests that an increase in temperature of 1°C over a five-year period, with no change in present precipitation patterns, would reduce mean annual runoff by 15% in the Oldman River basin. Such reductions in discharge would stimulate downstream channel aggradation, and locally derived valley-sediment input from storms might be predicted to exceed the carrying capacity of new discharge regime in the main streams. However, confidence in such predictions is low, because, at the large scale, no evidence exists to demonstrate a simple, direct relationship of rainfall to erosion and sediment yield (Walling and Kleo, 1979; Walling and Webb, 1983; Graf, 1988). Indeed, attempts to relate erosion and sediment yields in arid and semiarid regions to climatic indices using runoff or effective precipitation have proven futile (Bull, 1991), with changes in vegetation cover alone having the potential to mask precipitation trends. Moreover, in cases like the lower Red Deer basin especially, where a vast majority of the river's sediment load is derived from small areas, it is expected that increases or decreases in basin-wide precipitation will cause little variation in the already high badland erosion rates.

A change in climate to warmer and drier conditions should generally favour slope stability with respect to landsliding. Such conditions would serve to deplete groundwater and stream flow, two principal controls of slope failure. However, if a drier climate increases demand for irrigation water, slope instability associated with excess irrigation could increase in some places. Additionally, if the shift to a warmer and drier climate is accompanied by an increase in the magnitude and frequency of extreme hydroclimatic events, as might well occur with greater amounts of tropospheric heat, large infrequent storms and floods could trigger landslides. These would likely have a random spatial and temporal distribution and would be difficult to take into account from a land-management perspective.

The warmer/drier scenario has its greatest implications with respect to soil redistribution in the Palliser Triangle. A historical analogue for this scenario is the 1930s, when prevailing conditions of severe drought and inappropriate land-use practices led to widespread destabilization of soils. It is noteworthy, however, that the droughts of the 1930s were not as severe as others in the paleoenvironmental record, nor as severe as projected by some GCMs. Warmer and drier conditions would presumably lead to lower crop-residue inputs, higher incidence of fallowing and, in the most extreme cases, abandonment of individual farms. Crop cover in a drought year, and residue cover on fallow fields in the year following a drought, are greatly reduced, leaving the soil surface much more susceptible to wind erosion in the following spring or summer (Wheaton and Chakravarti, 1987). Moreover, the absence of a significant residual cover would also greatly increase the impact of high-intensity rainfall events in the following season.

Sandy to sandy loam Chernozemic landscapes (BC-cl, Fig. 12) have low moisture-holding capacities and would be most susceptible to drought and wind erosion associated with an increased moisture deficit. Dark Brown Chernozemic soils developed in loess south of Swift Current (DBC-lm, Fig. 12) would also be very sensitive to warmer/drier conditions. The effect of this scenario on the clay and clay loam Chernozemic landscapes (BC-c and BD-cl units, Fig. 12) and the Solonetzic landscapes south of Kerrobert, Saskatchewan would be in part mitigated by the high moisture-holding capacities (and hence drought resistance) of these soils.

Despite such regional differences, it is fair to conclude that the impacts of this scenario on soil erosion in all areas are likely to be severe. In the analogous conditions of the 1930s, all areas in the Brown zone were affected; in sandy areas and on Solonetzic soils the impact was permanent insofar as the land was taken out of crop production and put into pasture under supervision of the Prairie Farm

Rehabilitation Administration (PFRA). Areas of Chernozemic soils returned to crop production, but only because the climatic conditions moderated in the 1940s. Had warm and dry conditions continued into the 1940s, the impact throughout the Palliser Triangle would have been profound.

Scenario II – warmer and wetter

Geomorphic impacts under this scenario, as with scenario IV (cooler and drier), depend mainly on the magnitude and seasonality of the principal climatic elements. If increases in evapotranspiration produced by warmer temperatures are generally offset by increases in precipitation, minimal changes in available moisture or on geomorphic systems would result. However, if this scenario is associated with increases in the length of the growing season and higher atmospheric CO_2 levels, and effective moisture availability remains similar to present or increases, it may well have a positive impact on agricultural production within the Palliser Triangle and, more significantly, the Canadian prairies as a whole (cf. Canadian Climate Program Board, 1995).

Scenario III – cooler and wetter

A change in climate associated with decreased temperatures and increased precipitation would significantly increase moisture availability, which at present is the greatest limitation on regional sustainability. Nonetheless, associated decreases in the length of the growing season and total growing degree days could have serious negative impacts on agricultural production. Increased moisture would increase vegetation cover and reduce sediment availability for most geomorphic systems. Analogues for this interval in the paleoenvironmental record of the region are found in the Little Ice Age (ca. 1450-1800 AD) and Neoglacial (ca. 3000-1000 BP) intervals.

As eolian activity is driven by moisture availability, scenario III would lead to increased sand dune stabilization, as has been the general trend for most of the present century (David, 1993). Mobilization of sand dunes would likely only occur as a result of human disturbance, and would likely be short lived.

Although a cooler and wetter climate would undoubtedly increase stream discharge, these changes would likely be more linear than those predicted for the warmer and drier scenario. For example, in their analysis of the Oldman River basin, Nkemdirim and Purves (1994) estimate that a 1% increase in precipitation associated with present temperature regimes would increase streamflow by 1%. Significant increases in streamflow would result in more efficient sediment transport, increase the size of effective contributing areas, and lead to the development of a more integrated drainage network. Impacts upon sediment load are far less certain, with increased vegetation cover possibly serving to decrease sediment yields from most areas. However, many local badland areas, which presently contribute the vast majority of sediment to streams, would likely experience accelerated rates of erosion because vegetation cover in these barren, infertile landscapes is unlikely to increase significantly regardless of moisture availability.

The geomorphic system that is expected to show the greatest impacts under cooler and wetter conditions is mass wasting, in particular landsliding. Increased moisture availability would raise regional water tables and enhance slope instability. Similarly, increased stream discharges could lead to increased bank erosion which would in turn promote slope failure. Unlike landslides associated with extreme hydroclimatic events, the most probable locations (but not timing) of landslides under this scenario should be fairly predictable on the basis of geological parameters.

Impacts of soil redistribution in the Palliser Triangle would be expected to be reduced under this scenario, excepting those associated with extreme climatic events. This scenario of reduced moisture stress could potentially allow increased agricultural productivity in some areas as a result of more intensive cropping systems. In turn, greater crop residues and increased opportunities for crop rotation should reduce the severity of wind and water erosion. However, if the magnitude of cooling were similar to that associated with the Little Ice Age, associated decreases in the length of the growing season could present a new constraint to agricultural production (cf. Rannie, 1983).

Scenario IV – cooler and drier

Like scenario II (warmer and wetter), the impacts of this scenario are closely related to the magnitude and seasonality of principle climatic factors. If decreases in evapotranspiration associated with cooler temperatures generally offset precipitation decreases, minimal changes in available moisture or on geomorphic systems would result. Parts of the Little Ice Age may provide a paleoenvironmental analogue for this scenario. There is evidence for extensive sand dune activity towards the end of this interval (ca. 1800 AD) related to a severe moisture deficit when decreases in precipitation were apparently far more significant than those in temperature (Wolfe, 1996).

Summary

All of the major geomorphic systems in the Palliser Triangle will respond to changes in regional climate. Of the four simple climate scenarios considered here, impacts are expected to be greatest under conditions of increased warmth and decreased precipitation, ominously the conditions currently projected by most GCM simulations of a $2xCO_2$ world.

The most predictable geomorphic responses are associated with eolian and mass wasting processes. The eolian system is most sensitive, since it presently lies very close to climatic thresholds in the Palliser Triangle. Significant increases in sand dune activity are expected under a scenario of extended drought. On the other hand, any increase in moisture availability would result in continued sand dune stabilization, as has been the trend for much of this century. An increase in moisture availability would also promote landsliding by raising regional water tables and increasing fluvial undercutting. A decrease in moisture availability would lead to increased slope stability, with the exception of random landslides triggered by extreme hydroclimatic events.

Predicting general trends that a change in climate will exert on stream flow is possible, but since precipitation is such a fundamental component of the fluvial system and GCM estimates of precipitation changes are currently fraught with difficulties, such predictions remain equivocal. The effects of a change towards warmer and drier climate will be far more significant on stream flow than the case of a change to cooler and wetter climate. Attempting to predict the impacts on the fluvial geomorphic system, and in particular sediment yields and transport, is exceedingly complex and perhaps futile. Nonetheless, given that the vast majority of sediment to through-flowing streams is derived immediately adjacent to the river channels, these impacts will be largely restricted to floodplain environments. Otherwise, impacts may only be important in terms of how they influence processes of soil erosion.

In evaluating the sustainability of the Palliser Triangle from a geomorphic perspective, it is the numerous processes associated with agricultural soil redistribution that are of critical importance. Of the four climate scenarios considered, three have either have favourable or no significant impacts on soil erosion, and could in fact lead to increased agricultural productivity. However the scenario of greatly reduced moisture availability, conceivably far more severe than occurred during historical drought intervals, could have serious impacts on soil redistribution throughout the Palliser Triangle. The severity of these impacts, however, is as dependent upon the human response to climate change in terms of agricultural practices and land management as it is upon climate itself. Development of mitigation procedures can be assisted through detailed spatial analysis of landscape sensitivity in conjunction with modelling of geomorphic processes, as is being undertaken in the concluding phase of the Palliser Triangle IRMA.

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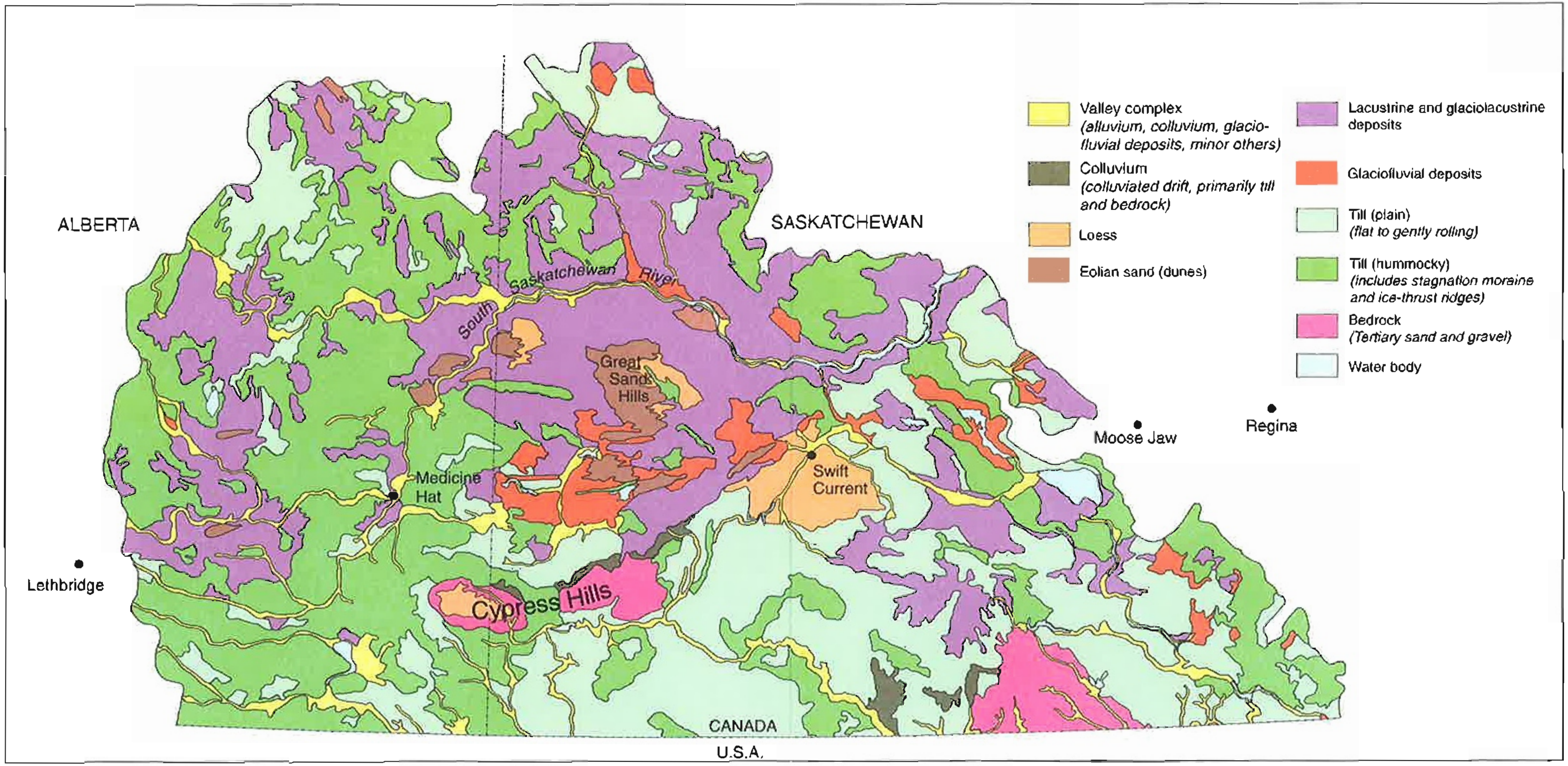

Figure 6. Simplified surficial materials map. See text for unit descriptions. Alberta data compiled from Shetson (1987), Saskatchewan data from David (1964), Klassen (1991, 1992b) and Saskatchewan Research Council (1986, 1987a, b, c).

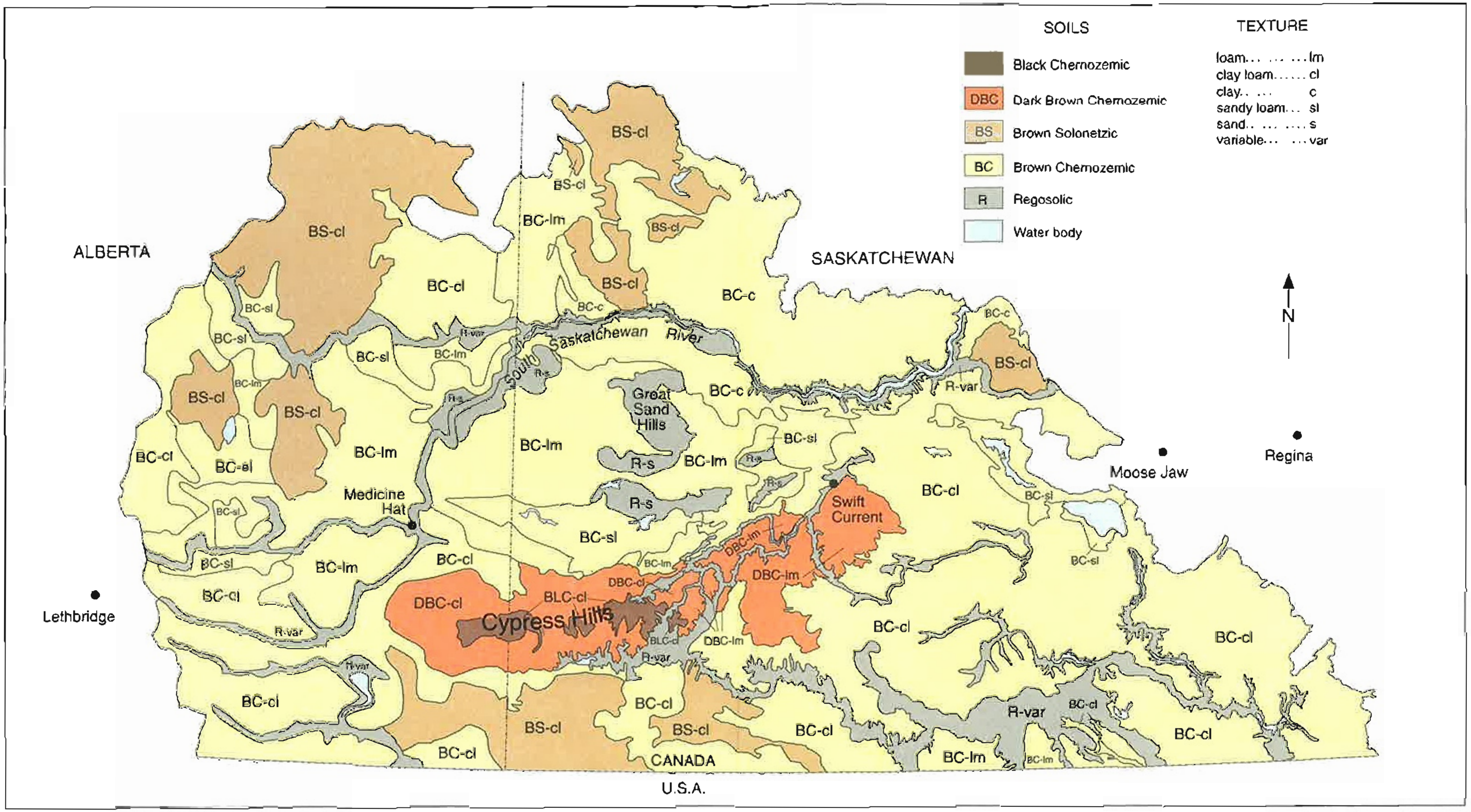

Figure 12. Major soil units in the Palliser Triangle. Polygons are generalized from the Soil Landscape Maps of Saskatchewan and Alberta (Canada Soil Inventory, 1987a, 1987b).

Compilation and drafting by D.S. Lemmen et al., 1997

0 km 100

Canada

Figures 6 and 12

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