

Impacts of Future Climate Change on the Southern Canadian Prairies: A Paleoenvironmental Perspective

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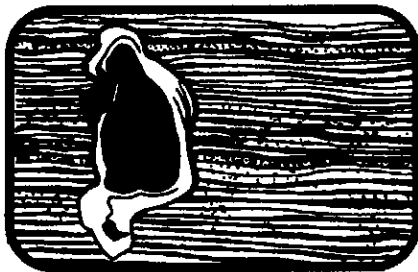
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Article abstract

Water and soil are critical to the prosperity of the southern Canadian prairies. Both have been strongly influenced by historic climate variability, and by even more significant climate changes that have occurred during the Holocene. These observations, together with general circulation model projections of increasing aridity in this region, raise concerns about the potential impacts of future climate change. Collaborative, multidisciplinary research conducted over the past five years as part of the Palliser Triangle Global Change Project has focussed on geoscientific aspects of climate change in the driest portion of the Canadian prairie provinces. Re-construction of past climates, based on multiple paleolimnological indicators (plant macrofossils, diatoms, ostracodes, algal pigments, sedimentology, mineralogy, and stable isotope geochemistry), demonstrates that the historic record of roughly 100 years does not adequately capture the range of climatic variability observed during even the last 2000 years. The re-sponse of hydrologie and geomorphic systems to past changes in climate documents a surprisingly dynamic landscape. The best analogues for projected future climates feature a regional water table more than 4 m below its present level and enhanced wind erosion. The paleoenvironmental record highlights the susceptibility of water and soil resources to climate-induced impacts that are likely to adversely affect human activities in the region over the next century.

Articles



Impacts of Future Climate Change on the Southern Canadian Prairies: A Paleoenvironmental Perspective

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SUMMARY

Water and soil are critical to the prosperity of the southern Canadian prairies. Both have been strongly influenced by historic climate variability, and by even more significant climate changes that have oc-

curred during the Holocene. These observations, together with general circulation model projections of increasing aridity in this region, raise concerns about the potential impacts of future climate change. Collaborative, multidisciplinary research conducted over the past five years as part of the Palliser Triangle Global Change Project has focussed on geoscientific aspects of climate change in the driest portion of the Canadian prairie provinces. Reconstruction of past climates, based on multiple paleolimnological indicators (plant macrofossils, diatoms, ostracodes, algal pigments, sedimentology, mineralogy, and stable isotope geochemistry), demonstrates that the historic record of roughly 100 years does not adequately capture the range of climatic variability observed during even the last 2000 years. The response of hydrologic and geomorphic systems to past changes in climate documents a surprisingly dynamic landscape. The best analogues for projected future climates feature a regional water table more than 4 m below its present level and enhanced wind erosion. The paleoenvironmental record highlights the susceptibility of water and soil resources to climate-induced impacts that are likely to adversely affect human activities in the region over the next century.

RÉSUMÉ

L'eau et le sol constituent deux éléments essentiels à la prospérité des régions de la portion sud des plaines canadiennes. Ces deux éléments ont été grandement affectés par les fluctuations climatiques de la période historique ainsi que par les fluctuations encore plus importantes durant l'Holocène. Ces observations ajoutées aux projections d'un accroissement de l'aridité dans la région à partir de modèle de la circulation atmosphérique générale soulèvent l'inquiétude quant aux effets possibles de changements climatiques à venir. Les recherches multidisci-

plinaires conjuguées effectuées au cours des derniers cinq ans dans le cadre du Projet des changements à l'échelle du globe dans le triangle de Palliser ont été concentrées sur les aspects géoscientifiques des changements climatiques de la portion la plus aride des prairies canadiennes. La reconstitution des climats d'autrefois basée sur une gamme d'indicateurs paléolimnologiques (macrofossiles de plantes, diatomées, ostracodes, pigments algaires, données sédimentologiques, minéralogiques et de géochimie d'isotopes stables) montrent que le registre des variations d'une centaine d'années n'est pas suffisamment étendu pour montrer toute fourchette des variations climatiques relevées pour la période des derniers 2000 ans. Les données accumulées montrent que la réponse des systèmes hydrologiques et géomorphologiques aux changements climatiques entraînent des changements de paysage plus importants que prévus. Les meilleurs modèles de prévision climatiques indiquent un abaissement du niveau régional de la nappe phréatique de 4 m et une augmentation de l'érosion éolienne. Les données paléoenvironnementales montrent que l'eau et le sol sont des ressources particulièrement sensibles aux effets de changements climatiques et que cela nuira grandement aux activités humaines de cette région au cours du prochain siècle.

INTRODUCTION

The economy of the southern part of the prairie provinces is one the most climatically sensitive in Canada (Wheaton *et al.*, 1992). Agriculture is the predominant economic activity throughout much of the region and is critically dependent on water and soil, resources that are directly affected by climate. Other economic sectors, including energy, recreation and wildlife, are also strongly influenced by climatic variability. Hence perturbations in climate could greatly affect the regional economy.

For example, during the drought of 1988, when mean annual temperature was 2–4°C above the 30-year mean and precipitation was roughly half the 1950–1980 average, a 29% decline in wheat production contributed to a \$1.5 billion drop in farm receipts in Saskatchewan alone (Wheaton and Arthur, 1989). Will such events become more common in the next few decades? Although long-term projections remain uncertain, general circulation model (GCM) simulations indicate that global warming resulting from increased greenhouse gas concentrations is likely to increase mean annual temperature and decrease summertime precipitation throughout the northern Great Plains (e.g., Karl *et al.*, 1991). It is possible that drought will become more frequent than it has been since the area was first settled by Eurocanadians, just over one hundred years ago. The geoscientific record, which contains evidence of frequent and severe drought in the recent geologic past, permits us to outline some possible impacts of future climate change, identify regions and resources at risk, and place projected global warming scenarios in the context of the region's long-term climatic history.

CLIMATE VARIABILITY AND CHANGE

The climate of the southern prairies is characterized by great variability on many time-scales. Temperature changes as great as 20°C in one hour have been reported in association with chinook winds

and, with an annual temperature range exceeding 80°C, the southern prairie region has the greatest seasonal temperature variation in Canada (Hare and Thomas, 1979). Although the driest parts of the region are classified as dry-subhumid using 30-year climatic means, periods of drought can produce true semiarid conditions over large areas. Drought has affected at least some portions of the southern Canadian prairies in almost every decade of the 20th century (Chakravarti, 1976).

The high variability inherent in this system makes evaluation of climate trends, which potentially reflect climate change, difficult. For the prairies as a whole, historic data show a statistically significant warming of 0.9°C for the period 1895–1991 (Gullett and Skinner, 1992), whereas precipitation shows no discernable trend (Bootsma, 1994). Continuous meteorological records for the southern prairies are available beginning in 1883 (Medicine Hat and Regina), with Maple Creek (1884) and Swift Current (1885) of similar duration (Fig. 1; Environment Canada, 1993). Development of proxy climate records (i.e. indirect measures of past climate based upon paleoenvironmental reconstructions) is the only means of extending this relatively short meteorological record.

Debate concerning future climate change tends to focus on whether recent and future human activity will have severe impacts on the climate system (anthropo-

genic climate “change”), or whether these impacts will be comparatively small in the context of larger scale fluctuations inherent to the climate system (so called “natural” climate variability). This debate will continue, despite the recent consensus that human influence is discernable in the recent historic climate record (IPCC, 1996). However, if the issue of concern is sustainability of climatically sensitive regions like the southern prairies, this debate assumes far less significance. Unless the historic record adequately reflects the range of climatic variability over a much longer period, it is unlikely that human activities have adapted to the variability that is probable in future climate (e.g., coping range; Smit, 1995). This point alone underscores the need for climate impact research, a need that is increased by the possible consequences of climate change resulting from human activities. Paleoenvironmental reconstructions represent a critical aspect of climate impact research by documenting the nature of landscape responses (e.g., hydrologic, geomorphologic and ecologic) to past climate change and variability. These reconstructions, in turn, can provide analogues for future climate impacts, including those associated with an enhanced greenhouse gas world.

THE PALLISER TRIANGLE GLOBAL CHANGE PROJECT

The Palliser Triangle, extending from

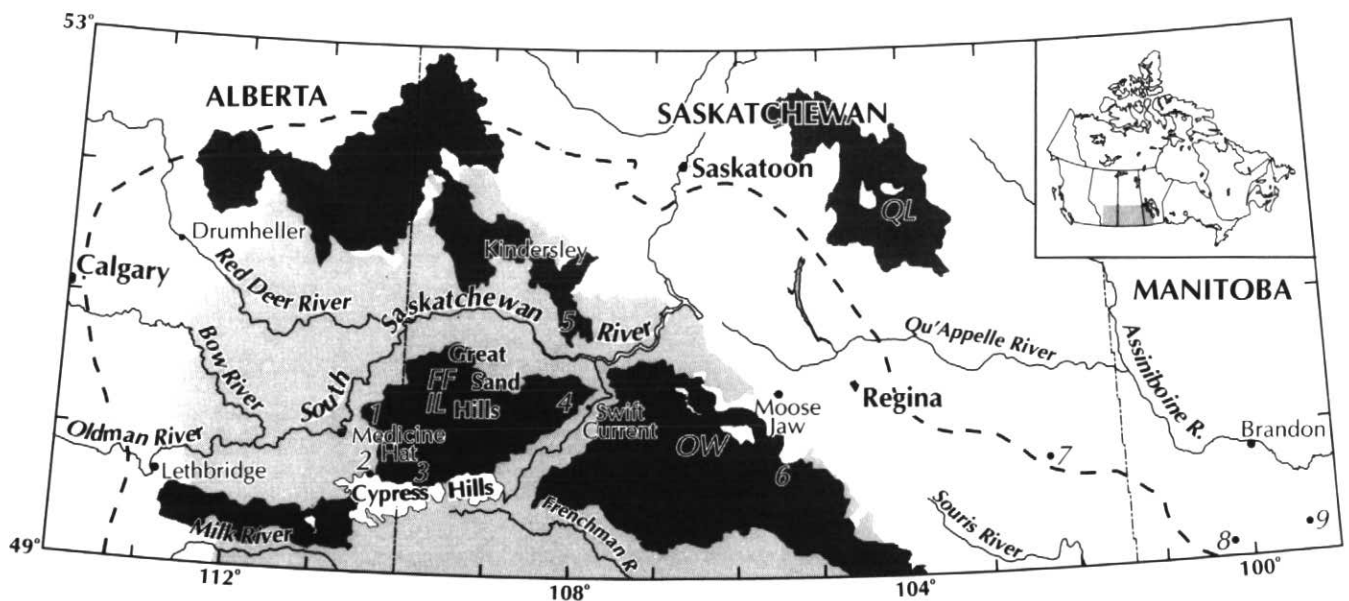


Figure 1. The Palliser Triangle (bold dashed line) as defined by John Palliser during his expedition of 1857 to 1860 (from Spry, 1968). The light shaded area is the Brown Chernozemic Soil Zone (see Fig. 4), the driest part of the region. Dark shading denotes areas of internal drainage. FF - Freeflight Lake; IL - Ingebright Lake; OW - Old Wives Lake; QL - Quill Lakes. Paleolimnological study sites are numbered 1–9, corresponding with descriptions in Table 1.

southwestern Manitoba to southwestern Alberta (Fig. 1), is the driest part of the Canadian prairie provinces and is characterized by a strongly negative annual moisture balance. It is named after Captain John Palliser, who declared this area of grasslands "forever comparatively useless" for agriculture during his survey of 1857-1860 (Spry, 1968). The fact that this region today forms much of the highly productive Canadian wheat belt is more a reflection of the variability of regional climate than a refutation of Palliser's observations. Unknown to Palliser, his expedition coincided with a period of drought on the prairies. Indeed, few residents would have questioned his assessment of their land during the severe droughts of the 1930s.

Recognition of the region's climatic sensitivity was heightened during the severe drought of the late 1980s and a number of new research initiatives were developed that focussed upon the economic and social impacts of climate in the region (*e.g.*, Wall, 1991; Wilhite and Wood, 1995). The Palliser Triangle Global Change Project was established in 1991 by the Geological Survey of Canada specifically to address geoscientific aspects of climate impacts on the southern prairies (Lemmen *et al.*, 1993). A series of workshops led to the development of a multidisciplinary collaborative program involving 31 researchers from government and universities. Emphasis was placed on the paleoenvironmental record of the last 2000 years, a period in which major atmospheric forcing (*e.g.*, orbital-driven solar variation, ocean temperature, albedo) has remained relatively constant. Data for this interval best represents the range of climate variability that may be anticipated in the near future, in the absence of significant climate changes related to increased concentrations of greenhouse gases. However, records of the entire postglacial interval were sought to derive possible analogues for future climate as predicted by GCM's, recognizing that the factors controlling past climates relate largely to orbital variations and not to greenhouse gas concentrations.

Three main research directions were identified: 1) past climatic and hydrologic changes; 2) relationships between climate and landscape processes; and 3) analysis of landscape sensitivity. Paleoenvironmental work was complimented with monitoring studies of modern processes whenever possible. Most research conducted as part of the project is now being ana-

lysed and synthesized for publication, and a comprehensive review of this research is beyond the scope of this article. Rather, the objective here is to outline the approaches used in this project using two examples; paleoenvironmental reconstructions based upon paleolimnological analyses, and landscape responses to climatic variability recorded in the eolian system. Insights derived from this work are then placed within the broader issues of regional climate change impacts.

PALEOENVIRONMENTAL RECONSTRUCTIONS

Prior to the establishment of the Palliser Triangle Global Change Project there was a scarcity of paleoenvironmental data from the Canadian prairie grasslands owing to numerous limitations inherent to this region (*e.g.*, Barnosky *et al.*, 1987). Tree ring records, the most reliable source of annual resolution proxy climate data, were available only from forested uplands on the Cypress Hills (Fig. 1), and are limited to less than 220 years duration (Sauchyn and Porter, 1992). The most widespread sources of long-term (millennial-scale) paleoenvironmental data are the vast number of lakes that dot the prairie landscape. Although the lakes are ubiquitous and can provide exceptionally detailed records of past physical and chemical conditions, they are often less than ideal paleoecological sites because they tend to be ephemeral and highly saline, thus containing discontinuous sedimentary records and a limited range of biological proxy indicators. As a result, considerable effort was devoted to finding sites best suited to the Project's objectives. Most important was that the lake did not often completely dry up. In groundwater discharge areas (*e.g.*, most of the plains), only lakes fed by shallow ground water with significant aquifer capacity are immune to frequent desiccation. Significantly less than 1% of the lakes in the Palliser Triangle lie within such settings.

The climatic sensitivity of many prairie lakes is documented by historic lake-level fluctuations (Fig. 2). Lake levels are also direct indicators of hydrologic changes, and water is arguably the most critical resource of the southern prairies. Changes in shoreline position are reflected in sedimentary records by changes in lithology and plant macrofossil assemblages. Macrofossil assemblages are also helpful indicators of lake salinity, with species typical of saline and/or ephemeral ponds being key indicators of low lake levels and

extended dry conditions, and provide material suitable for radiocarbon dating (Vance, 1991). Plant macrofossil and lithostratigraphic (mineralogy, particle size, geochemistry) analyses of each lake sediment core collected formed the basis for paleoenvironmental reconstructions, and were supplemented at selected sites by biolimnological indicators including diatoms, ostracodes and pigments, as well as stable C and O isotope analyses of both sediments and calcareous microfossils (Vance, 1997).

Saline Lakes

The hydrologic landscape of the Palliser Triangle is characterized by poorly integrated drainages and vast numbers of lakes and wetlands. Large tracts of hummocky and ice-thrust moraine, in combination with the limited efficacy of Holocene fluvial processes under subhumid to semiarid climates, results in more than 45% of the region being internally drained (Fig. 1; Campbell, *in press*). Ground water dominates the hydrologic budgets of most lakes, and provides drinking water for about 90% of the region's rural population (Hess, 1981). It is also the source of dissolved ions entering lakes, originally derived from bedrock and glacial deposits. The strongly negative annual water balance concentrates these ions and produces lake salinities that may exceed 400‰. The few fresh water lakes that occur in the region invariably occur in groundwater recharge settings on uplands, or through-flow settings on the plains.

A conservative estimate of 1.5 million saline lakes in the Palliser Triangle reflects a density and diversity of salt lake environments unequalled in the world (Last, 1989). Although a great majority of these lakes are playas (small, shallow and ephemeral), the region also includes some of the largest (Quill, Old Wives) and deepest (Freefight) salt lakes in North America (Fig. 1). Virtually all water chemistry types are represented, with Na-Mg-SO₄ brines dominant (Last, 1992). Over 80 species of endogenic precipitates and authigenic minerals have been identified, the most common being calcium/calcium-magnesium carbonates and sodium/sodium-magnesium sulfates. Halite, gypsum and calcite, which are common in most salt lakes of the world, are relatively rare in the lakes of the Palliser Triangle owing to their brine chemistries.

This diversity in modern hydrochemistry and sediment mineralogy offers high potential for detailed reconstruction of past

lake environments based upon geochemical and mineralogical analysis of sediment cores. While interpretations most commonly focus on physical and chemical limnology (*e.g.*, water stratification, depth and chemistry), it is also possible to obtain reliable estimates of past climatic conditions (Shang, 1997). For example, detrital mineralogy reflects the intensity of weathering in the watershed, which in turn is controlled largely by the amount of precipitation. Higher ratios of detrital components such as dolomite to calcite, quartz to feldspars, and orthoclase to plagioclase indicate more intense weathering due to removal of the more soluble minerals and enrichment of the chemically stable fraction. Additionally, endogenic mineralogy directly reflects lake hydrochemistry, which is largely controlled by climatic factors such as evaporation/precipitation ratio, temperature, and vapor pressure. Reconstructions are aided by the fact that most salt lakes feature comparatively high

evaporite sedimentation rates (approaching $1 \text{ cm}\cdot\text{a}^{-1}$). Ingebrigt Lake (Fig. 1) contains over 50 m of salt, the thickest Holocene evaporite deposits known in North America (Last, 1991). Sediment traps in these lakes have recorded remarkable rates of modern deposition approaching $60 \text{ kg}\cdot\text{m}^{-1}\cdot\text{a}^{-1}$, with most of the material consisting of soluble endogenic salts (Last, 1993a). Additionally, many sedimentary records from these lakes are laminated (often discontinuously), offering greater potential for high resolution reconstructions (Fig. 3; Last and Vance, 1997). Caution must be applied in such analyses, however, as the temporal significance of laminations is largely unknown. Rather than reflecting seasonal or annual changes in sediment influx (*e.g.*, varves), laminations in saline lakes generally record discrete precipitation events related to the geolimnology of the water body. Several laminae may be deposited within a single year, while in other years

none will be produced. However, it has been demonstrated that in some lakes deposition of laminated sediments corresponds to periods of low water coincident with drought (Vance *et al.*, 1992), offering potential for highest resolution reconstructions at times of greatest interest from the perspective of agricultural sustainability.

Despite the advantages of saline lakes for paleolimnological reconstructions, several important difficulties with such lakes also must be noted. Most basic is the fact that many of these lakes are intermittently dry and subject to periodic desiccation and deflation. Caution must be taken to ensure that any major unconformities, which are potentially very difficult to identify, are recognized in the sedimentary record. Secondly, the high salinities of many basins restrict the biological diversity of these water bodies, thereby limiting the number of biological indicators available for study. This is particularly true for siliceous and calcareous microfossils

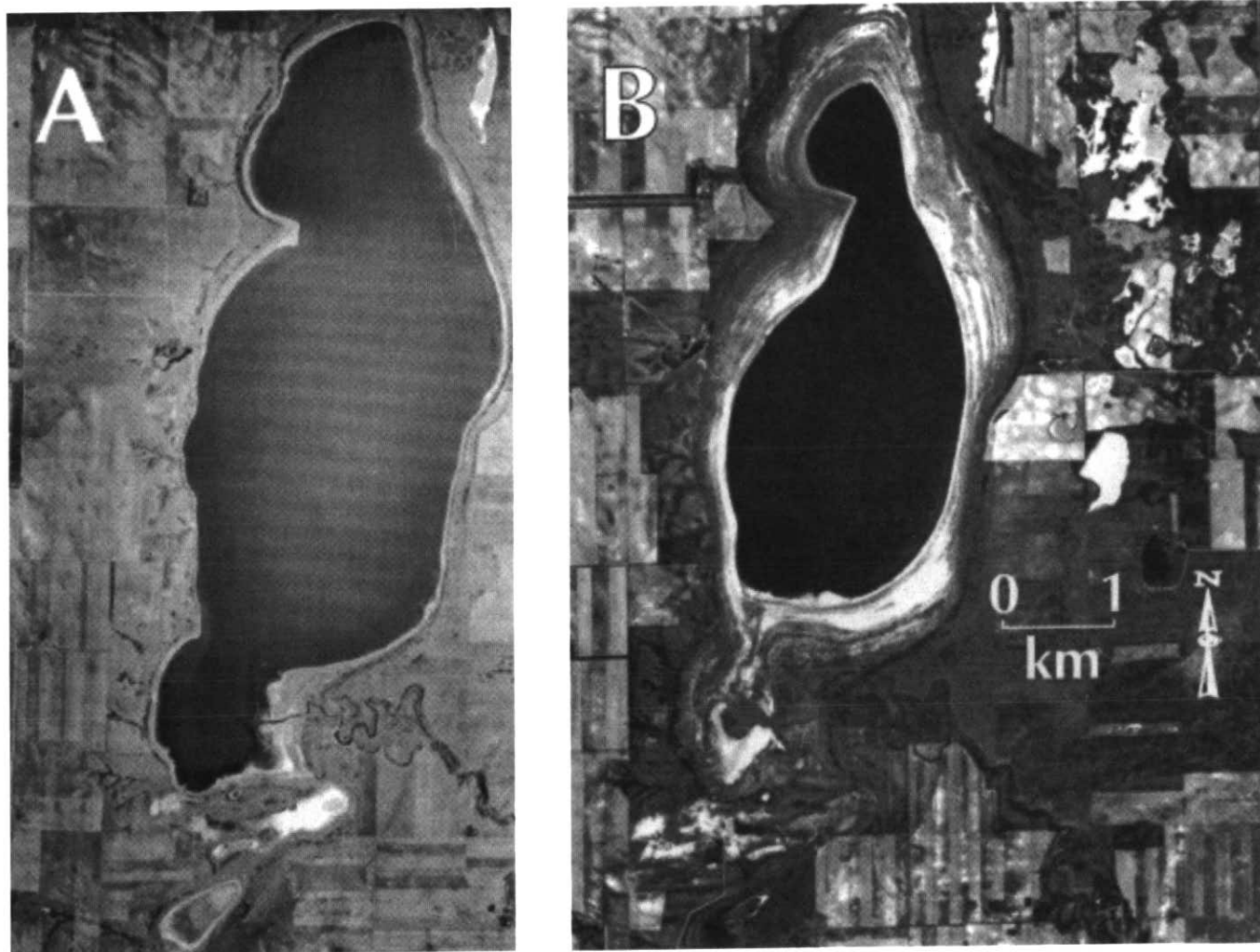


Figure 2 Vertical air photographs of Antelope Lake (site 4, Fig. 1) showing dramatic drop in water level over three decades: (A) 1961; (B) 1991.

(diatoms and ostracodes). Thirdly, chronological control of sedimentary records tends to be limited to ^{14}C and ^{210}Pb dating. Although the AMS (accelerator mass spectrometry) radiocarbon dating technique makes it possible to date very small samples, suitable material is still comparatively scarce in most lacustrine cores recovered from the Palliser Triangle. Finally, well documented post-depositional

changes can occur in the sediment record as the result of mineral diagenesis, salt dissolution, karsting and mud diapirism, all with potential to disrupt sedimentary sequences (Last, 1993b).

Results

Nine lakes were chosen as primary sites for multiple indicator analyses, with multiple cores collected from each site (Fig. 1,

Table 1; Vance, 1997). These lakes follow both east-west and north-south transects, and include both fresh water lakes from groundwater recharge areas on major uplands as well as saline lakes from groundwater discharge areas on the plains. Even with the considerable effort given to site selection, only one lake from the plains (Oro Lake) appears to contain a complete, uninterrupted Holocene sedimentary record (Table 1).

In general, the record of postglacial climate and hydrologic changes from these sites shows three broad periods. Records of the early Holocene (prior to ca. 7500 BP) are only available from four lakes (Clearwater, Oro, Harris and Killarney; Fig. 1, Table 1). These records suggest an interval of rapid changes in both lake levels and water chemistry. Both Clearwater and Harris lakes show evidence of fluctuating high to very high Mg/Ca ratios, reflecting changes between essentially fresh and hypersaline conditions (Last and Sauchyn, 1993; Last *et al.*, submitted). These fluctuating conditions most likely record hydrologic events that may not necessarily be climate-driven. Other paleolimnological indicators (diatoms and algal pigments) suggest that neither of these basins, located in groundwater recharge and through-flow sites, are particularly sensitive to relatively minor changes in climate (Wilson *et al.*, 1996), such as those experienced in the last one hundred years (Leavitt *et al.*, in press).

The mid-Holocene, extending from about 7500 to 4000 BP, is at least partly recorded in all of the principal study sites except Max Lake (Table 1). Plant macrofossil data from all sites analysed document lake levels at this time far below present lake levels. At both Clearwater and Killarney lakes, this interval includes major unconformities in the central basin cores suggesting that these lakes, presently 9.4 m and 5.9 m deep, may have dried completely (Vance, unpublished). Similarly, the absence of a sedimentary record for most of this interval at Kenosee, Antelope and Max lakes also suggests that they were dry. Even at the end of this period the level of Kenosee Lake, which lies in a groundwater recharge site, lay 5 m below its present level (Vance *et al.*, 1997). A conservative estimate would place the regional water table at least 4 m below its present level for much of this time interval.

Because mineral assemblages of mid-Holocene sediments, commonly dominated by gypsum, mirabilite, magnesite

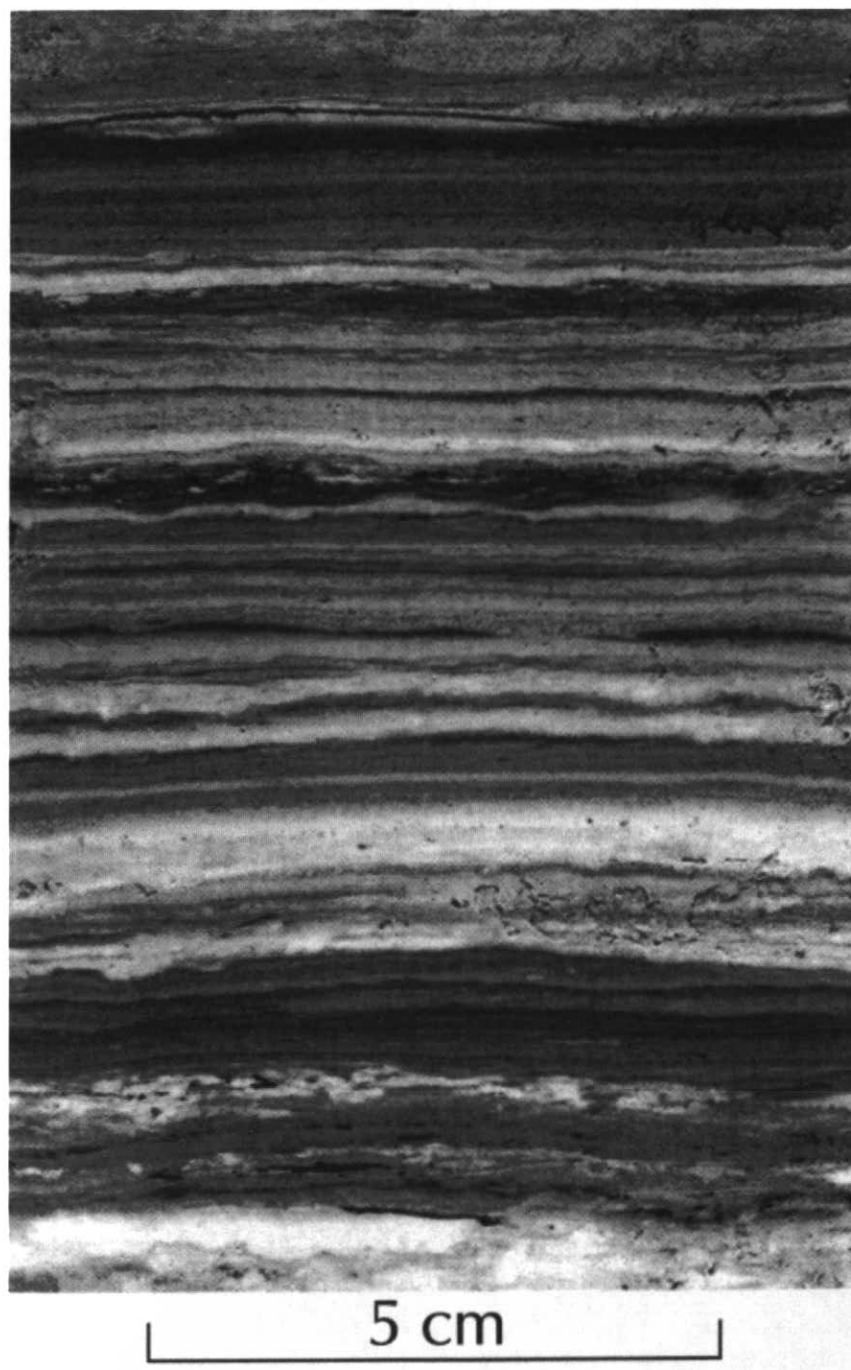


Figure 3 Finely laminated mid-Holocene sediments from Chappice Lake (site 1, Fig. 1). Individual laminae are comprised of aragonite, calcite, dolomite, magnesium calcite, hydro-magnesite, protodolomite or pseudohydromagnesite. Sediments are part of a 170 cm thick sequence recording extensive periods of drought between ca. 6000 and 4000 years BP.

and protodolomite, record deposition in hypersaline brine pools, and the plant macrofossil data indicate very low lake levels, markedly increased aridity is inferred for this period (e.g., Last and Vance, 1997). Ostracode and stable isotope data similarly record hypersaline conditions at sites that are presently sub-saline or fresh (e.g., Vance *et al.*, 1997). Climate transfer functions based on pollen data just beyond the periphery of the Palliser Triangle suggest that the period 5000-7000 years BP was characterized by mean summer temperatures 2°C warmer than present, and growing season precipitation 15% less than present (Vance *et al.*, 1995). This aridity is reflected in Chappice Lake by thick sequences of laminated sediments (Fig. 3). The thickness of these laminated sequences, when compared to those deposited during the historic drought decades of the 1880s and 1930s, indicates that drought conditions prevailed for several decades to centuries during the mid Holocene (Vance *et al.*, 1992).

Late Holocene (ca. 4000 years BP to present) sediments from most of the principle study sites reflect Neoglacial conditions generally more humid (cooler and/or wetter) than at present. Lake levels throughout the region increased beginning ca. 4500 years BP, with a period of peak effective moisture between 3000 BP and 1000 BP, during which there is little evidence of severe drought. 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), is recorded at the most climatically sensitive sites. The thicknesses of laminated sequences deposited at this time suggest that this event was characterized by drought intervals of several decades; more severe than those of the historic record but far less severe than those of the mid-Holocene (Vance *et al.*, 1992). A subsequent return to generally cooler and moister conditions than at present through the Little Ice Age (ca. 1450-1850 AD; Luckman *et al.*, 1993) is recorded across the region by high lake levels and comparatively fresh water conditions (Vance *et al.*, 1992, 1997). The present century appears unique within the last 2000 years in terms of its variability between short term drought and more humid conditions.

From a paleolimnological perspective, Project results highlight the value of using multiple proxy indicators. Traditionally, such studies rely heavily on a single indicator and utilize transfer functions based upon modern distributions to provide

Table 1 Primary paleolimnological study sites of the Palliser Triangle Global Change Project. Site numbers correspond to Figure 1; analyses conducted on multiple cores from each site.

No.	Name	Lat./Long.	Elev. (m asl)	Max. Depth* (m)	Surface TDS ^b (g L ⁻¹)	Core length ^c (m)	Basal Date ^d	Unconformities	Analyses ^e
1	Chappice	50°10'N/110°22'W	730	0.32	121-165	8.7	7325±70	Yes	S,M,G,I,MA,P
2	Elkwater	49°39'N/110°18'W	1209	8.3	0.25-0.30	5.5	4940±70	No	S,M,G,MA,O
3	Harris'	49°40'N/109°54'W	1234	1.4	0.17-0.32	7.7	8060±80	No	S,M,G,I,MA
4	Antelope	50°15'N/108°24'W	742	5.7	16.4-23.2	9.6	9240±240	No	S,M,G,MA,D,O,P
						4.5	1850±70	No?	S,M,G,I,MA,A
5	Clearwater	50°53'N/107°55'W	680	9.4	0.87-1.21	3.2	3430±80	No	S,M,G,I,MA,A
						7.7	9980±70	Yes	S,M,G,I,MA,D
6	Oro	49°47'N/105°20'W	700	6.4	17.5-40.2	8.1	9420±230	No?	S,M,G,I,MA,D,O,PM
7	Kenossee	40°49'N/102°18'W	735	4.3	2.07-3.63	2.0	4090±110	No	S,M,G,I,MA,O,A
8	Max	49°05'N/100°09'W	665	3.5	0.26-0.34	3.8	3330±70	No	S,M,G,MA,D,O,A
9	Killarney	49°11'N/98°42'W	490	5.9	0.44-0.64	4.2	9180±80	Yes	S,M,G,I,MA,D,A

^a maximum depth recorded during water chemistry sampling

^b range of total dissolved solids observed in surveys conducted in August 1994, January 1995 and May 1995

^c refers to core collected from the central basin of each lake. A nearshore core from Clearwater Lake is included because it is much longer and older than the core collected from the central basin.

^d in radiocarbon years, determined by accelerator mass spectrometry (AMS) dating of shoreline and terrestrial plant macrofossils. In most cases, dated sample lies above base of core.

^e analyses: S - sedimentology (includes particle size, water content and organic matter); M - mineralogy; G - geochemistry; I - stable isotopes; MA - macrofossils; D - diatoms; O - ostracodes; A - algal pigments; P - pollen; PM - paleomagnetism

^f includes analyses of 9.6 m long core collected prior to start of Palliser Triangle Global Change Project (Sauchyn and Sauchyn, 1991; Last and Sauchyn, 1993; Wilson *et al.*, 1996)

quantitative estimates of past environmental conditions (e.g., Smol *et al.*, 1994). Studies conducted as part of the Project include examples in which different indicators suggest markedly different conditions for the same time interval, unequivocally demonstrating that the single indicator approach has limitations. Resolving such apparent contradictions may lead to a more complete understanding of past environments, as was the case in recently completed work on Kenosee Lake (Fig. 1; Vance *et al.* 1997). Analyses of sediment mineralogy, plant macrofossils, ostracodes and stable isotopes from the lake cores produced a consistent reconstruction for most of the 4100 year record. However, mineralogy, ostracodes and isotopes all suggested that a high salinity event occurred at 2500 BP, commonly interpreted to reflect low water levels and increased aridity, whereas plant macrofossils for the same interval in near shore cores indicated a rapid rise in lake level, suggesting a more humid climate. All observations can be accommodated by the interpretation that this interval records a flush of highly saline ground water into the lake basin following an extended dry interval. Hence, the most reasonable interpretation that accommodates all lines of evidence is that this represents a climatically driven hydrologic event, which would not have been recognized in an interpretation based upon any single indicator.

Conclusions

Much of the paleolimnological research conducted through the project is now being published, and regional correlations and syntheses remain to be completed. Nonetheless, it is possible to summarize some of the more important conclusions based upon results to date, as they relate to the potential impacts of future climate change.

1) It is clear that the brief historic meteorological record does not capture the full range of climatic variability that may occur under present climate forcing factors. Within the last 2000 years there have been periods of both significantly greater and lesser aridity than have occurred in the last one hundred years. Hence it is unlikely that human activities are adequately adapted to climate variability, even in the absence of future climate change.

2) Lake levels and water quality on the southern prairies have responded to past global climate changes, with major climatic events such as the mid-Holocene warm interval, the Neoglacial, the Medi-

eval Warm Period, and Little Ice Age evident in the majority of records available. Therefore it is reasonable to conclude that future climate changes, resulting from both natural and anthropogenic forcing, will also affect this region.

3) The period 5000 to 7000 years BP may be the most appropriate analogue for GCM projections of future prairie climate. Although enhanced aridity at this time was a product of orbital forcing rather than greenhouse gas concentrations, it is noteworthy that under this climate the regional water table lay about 4 m below present levels, with the vast majority of surface water bodies having dried up and those remaining being predominantly hypersaline. This analogue highlights the vulnerability of water resources on the prairies and raises serious concerns about the sustainability of many activities under such a climatic regime.

LANDSCAPE RESPONSE

Data from sediment cores and other sources provide important insights into the nature of past climatic and hydrologic changes. One goal of the Project, however, is to evaluate what impacts these changes had on active geomorphic processes in the region, in order to better predict potential hazards associated with future climate change. A common perception of the southern prairies is that of a flat landscape, geomorphologically inert. For certain processes and spatial scales, such as regional fluvial systems, this perception may be warranted (Campbell, in press). Nonetheless for processes dominant at scales most relevant to human activities, such as local soil erosion, studies have demonstrated that this is a dynamic landscape characterized by extensive redistribution of material, although net exports are relatively limited (e.g., Pennock and DeJong, 1991).

Studies of past landscape responses provide important insights into relationships between geomorphic processes and climate (e.g., Vreeken, 1996), as well as outlining the relative sensitivity of geomorphic systems (Lemmen and Vance, in press). Field sites for geomorphic studies were clustered near the central, most arid part of the Palliser Triangle (Fig. 4), on the assumption that drier regions will be most climatically sensitive, and that these same regions may serve as an analogue for much larger areas of the prairies under GCM-projected future climates. In a review of regional geomorphic systems, Lemmen *et al.* (in press)

conclude that eolian environments have the most predictable response to climatic variability. Furthermore, the Palliser Triangle represents the most climatically sensitive eolian environment in Canada (Wolfe and Nickling, 1997).

Eolian Systems

Eolian deposits, including loess, cliff-top loams, and sand dunes, are widespread across the southern prairies. Sand dunes alone cover more than 3500 km² and include the largest contiguous occurrence of sand dunes in southern Canada, the Great Sand Hills of southwest Saskatchewan (David; 1993). The sensitivity of sand dune activity to moisture availability makes the dunes an important, and easily monitored, geologic indicator of climate variability (Vance and Wolfe, 1996). In addition, changes in dune activity are a reflection of regional changes in wind erosion, with important implications for agriculture.

All sand dunes in the Palliser Triangle are part of the parabolic dune assemblage (David, 1977; in press). The classic parabolic sand dune consists of a slipface that is convex in plan view and wings that extend upwind of the dune head (Fig. 5). Commonly, vegetation is viewed as the critical factor leading to the formation of parabolic dunes (e.g., Cooke *et al.*, 1993; Lancaster, 1995). However, David (1978) argued that it is moisture that leads to the parabolic morphology owing to increased cohesion between sand grains. Considered "wet" sand dunes, the moisture content of parabolic dune sands in the Great Sand Hills typically ranges between 4% and 8% by weight, a strong contrast to "dry" barchan dunes of hot desert regions (e.g., Mohave Desert of California). Moisture content is in turn a reflection of regional climate, and active parabolic dunes are typical of semi-arid and subhumid regions (David, in press).

At present, less than 0.5% of sand dunes in the Palliser Triangle are active (cf. Epp and Townley-Smith, 1980), with most activity confined to small blowouts within stabilized parabolic dunes. Considering the high wind regime of the southern prairies, which exceeds that of most of the world's hot deserts (Muhs and Wolfe, in press), it is clear that these eolian systems are supply-limited, owing primarily to the effects of vegetation and moisture. Air photos document changes in dune activity over the past several decades, with increasing vegetation cover producing a general trend towards re-

duced activity and dune stabilization. This trend was interrupted in some areas by an increase in active sand cover associated with the severe drought of the late 1980s (Wolfe *et al.*, 1995). Prior to the Project there was little chronologic data documenting past episodes of sand dune activity, and no data whatsoever for the most arid Great Sand Hills region.

Three techniques were used to elucidate past sand dune activity: 1) radiocarbon dating of organic material found within dunes; 2) archeological dating based upon diagnostic artifacts recovered within eolian sequences; and 3) optical dating of dune sand. The first two techniques provide important paleoenvironmental information, but relate to periods of dune stability rather than activity. Opportunities for radiocarbon dating are limited because buried organic soils, commonly exposed in dunes near the margin of the Palliser Triangle, are rare in the Great Sand Hills (Muhs and Wolfe, in press). Similarly, although artifacts are fairly common in active blowout dunes, they tend to be concentrated as a lag at the base of the blowout and only rarely related to a specific stratigraphic horizon. In contrast, optical dating provides an age of the last time

sediment was exposed to sunlight (Huntley *et al.*, 1985), and hence relates to periods of eolian activity. The technique is based upon that fact that defects exist within quartz and feldspar crystals that trap electrons released by ionizing radiation. The electron traps are emptied upon exposure to sunlight, whereas radiation after burial causes them to be repopulated. The age of buried sediments can be calculated through determination of the "number" of electrons present (actually a quantity proportional to this number) and the radiation dose rate responsible for their emplacement. Most eolian sediments are ideal for optical dating studies, and can yield ages of sufficient resolution to allow detailed stratigraphic analysis (see Huntley and Lian, in press, for discussion of potential problems and unexpected ages).

Results

Geochronologic data have been obtained from seven sand dune sites in the Great Sand Hills region (Fig. 4). Radiocarbon ages range from modern to 2620 BP, optical ages from modern to 970 calendar years before present, and most artifacts relate to occupations between *ca.* 2000 to 4000 BP. From these data, Wolfe *et al.*

(1995) tentatively conclude that periods of dune stability occurred from about 200 to 600 years ago and, based on basal deposits, around 2600 BP. The fact that all dates lie within the Late Holocene suggests that sand dune activity during this period has been sufficient to rework any older deposits. Mid and Early Holocene dates are also absent from sand dunes near the margin of Palliser Triangle (David, 1971; Campbell, 1997). Most striking, however, is that fully 85% of the optical ages obtained fall within the last 200 years. All of these dates relate to formerly active parabolic sand dunes (as opposed to active blowouts which typify the region at present) that are presently stabilized, and therefore indicate a significantly more active eolian environment in response to a drier climate. In the most detailed geochronologic study of a single site, David *et al.* (in press) document synchronous migration of dunes in the Seward Sand Hills (Fig. 4) from about AD 1802 to AD 1895. Average rates of dune migration during most of this interval were roughly 2-3 m·a⁻¹. These rates are comparable to monitored rates of slipface advance of presently active parabolic dunes elsewhere in the Palliser Triangle, as well as estimated rates

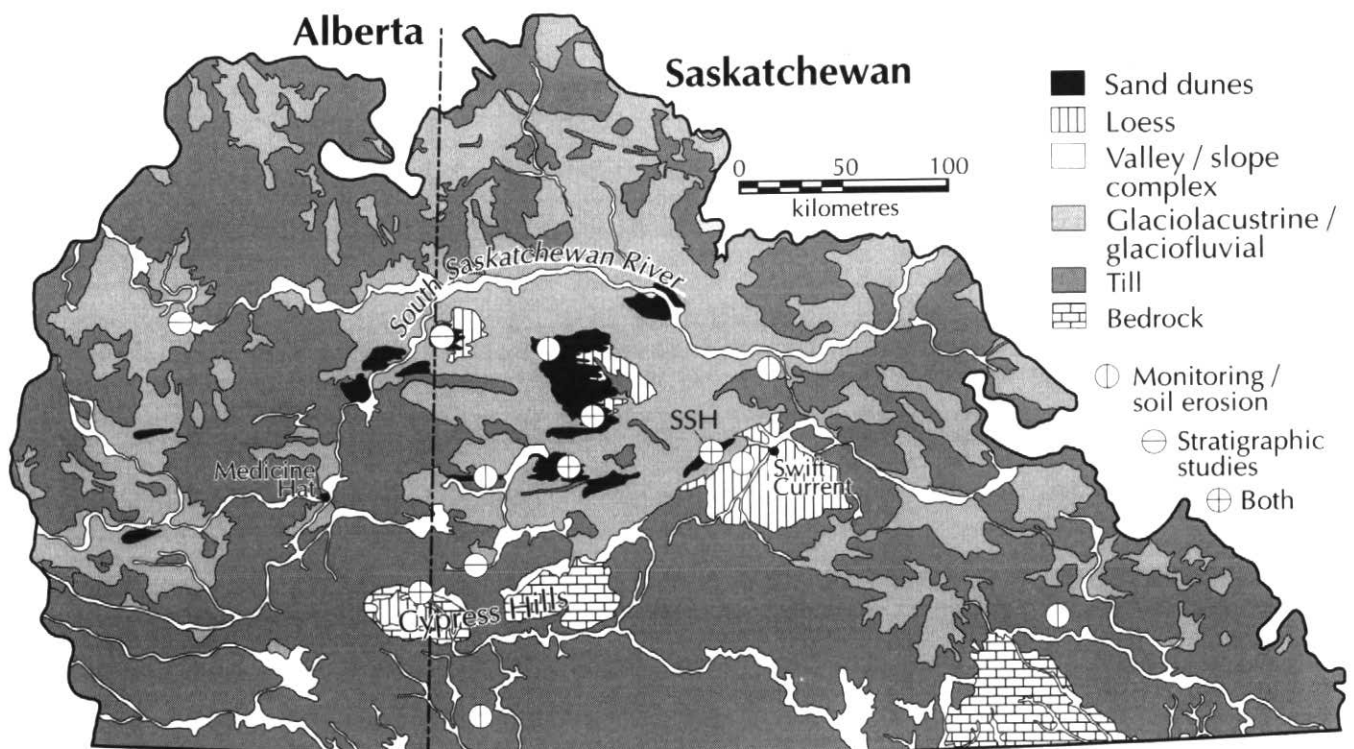


Figure 4 Simplified surficial materials map for the Brown Chernozemic Soil Zone, the driest part of the Palliser Triangle (Fig. 1). White circles denote locations of project study sites (see legend) and focus on the most geomorphically active environments. Sand dune occurrences are under represented owing to the small size of many fields. SSH - Seward Sand Hills.

of postglacial dune migration (Wolfe and Lemmen, in press).

As dune activity predominantly reflects moisture availability, this most recent period of extensive sand dune activity must relate to an interval of greater than present aridity. While there is little evidence in the regional paleolimnological record

suggesting a dry interval at this time, tree ring records from both the Cypress Hills (Sauchyn and Porter, 1992) and the foothills of the Rocky Mountains (Case and MacDonald, 1995) document a significant drought beginning about 1790 that was more severe than any in the instrumental climate record. The lack of corroborating

paleolimnological evidence of this event likely relates to the fact that it occurred near the end of the Little Ice Age, such that lakes fed by fully charged aquifers were not highly impacted by the drought. A lag between the onset of the drought and the dated activity of sand dunes reflects the response time necessary to ac-

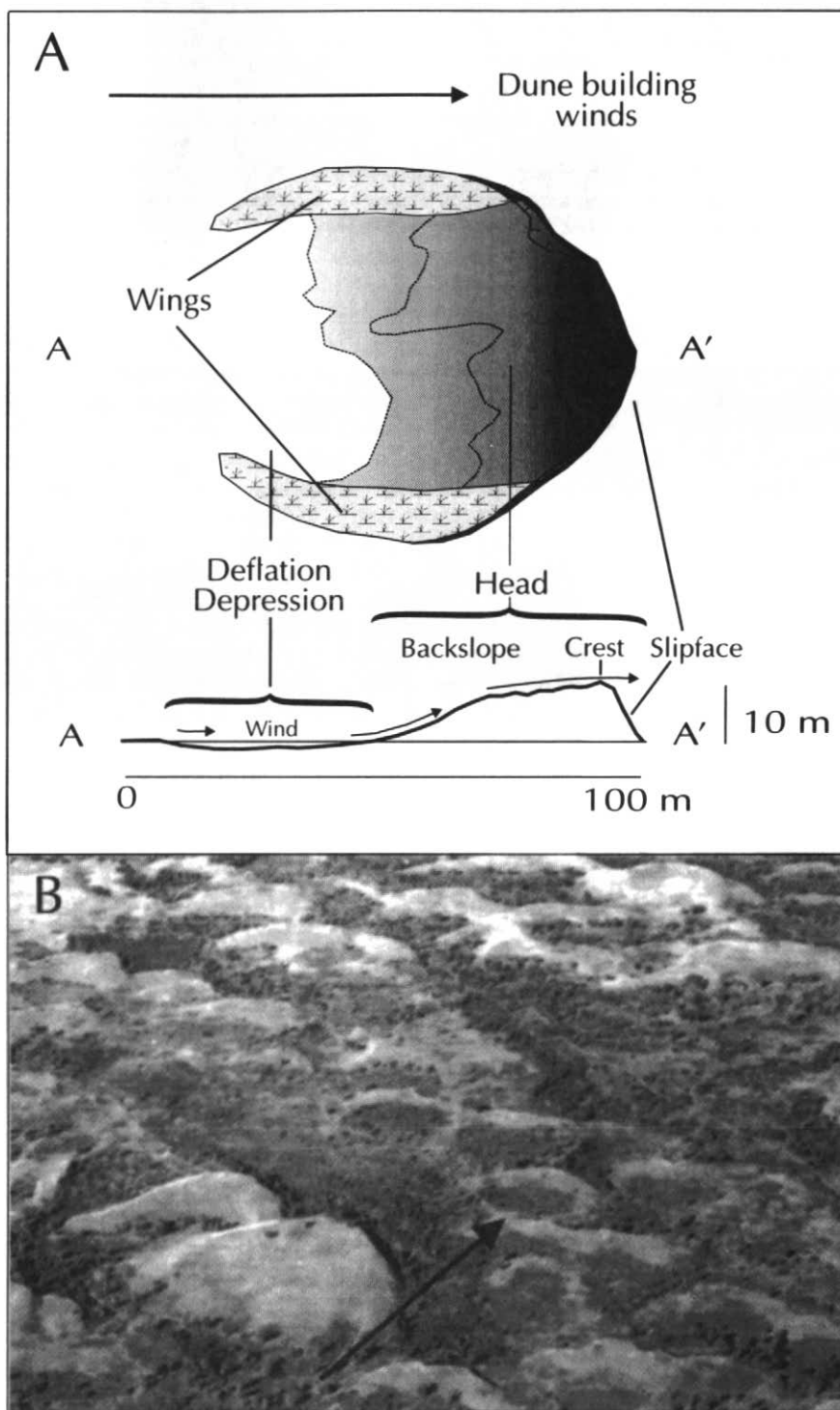


Figure 5 (A) Morphological features of an active parabolic dune (modified from Wolfe and David, 1997). (B) Oblique air photo of stabilized parabolic dunes in southern part of Great Sand Hills. Arrow denotes direction of dune building winds, large dune to left of arrow is about 120 m wide. View toward the ESE.

tivate fully stabilized dunes (David *et al.*, in press). Extensive eolian activity continued for most of the 19th century, with the last major pulse associated with the historically documented drought of the 1880s. Comparatively humid conditions associated with increased rainfall, that characterized much of the next three decades as well as the middle of the present century, limited sand dune response to the 1930s and 1980s drought to activity levels far less than those of the early 19th century.

Conclusions

1) Despite minimal changes in sand dune activity during this century, optical dating of dune sands provides unequivocal evidence of recent, regionally extensive sand dune activity in the 19th century. This activity most probably occurred in response to a drought that was more severe than any in the historic period, but less severe than those recorded earlier in the paleolimnological record. This highlights the sensitivity of eolian systems, and supports previous studies suggesting that much of the northern Great Plains lie near a threshold of extensive eolian activity (*e.g.*, Madole, 1994; Muhs and Holiday, 1995).

2) Although there is no direct evidence of sand dune activity during the interval 5000 to 7000 BP, the sensitivity of eolian systems to regional water balance suggests this must have been an interval of extensive sand dune activity. The absence of dune deposits dating to this interval simply reflects the fact that dune sands have been reworked since this time. Modelling of dune response to possible future climate scenarios indicates that presently stabilized dune areas of the Palliser Triangle are likely to be characterized by nearly continuous areas of active dunes (Wolfe, 1997; Wolfe and Nickling, 1997). This would not only have a direct impact on agriculture through the loss of grazing land, but also would affect the infrastructure of other resource sectors (*e.g.*, energy, transportation) that cross dune areas.

DISCUSSION

Context for Changing Climate

Timescales associated with geoscientific research provide a unique perspective on the controversies associated with issues of future climate change. Systems that appear relatively stable on the basis of recent human experience have been shown to be extremely dynamic when longer time scales are considered. In the

case of the last 2000 years in the southern Canadian prairies, the brief (100 year) historic climate record coincides with what appear to be uncommonly favorable climate conditions for agriculture. Even though climate through much of the last millennium generally has been cooler and more humid than present, drought periods of longer duration and greater intensity than any this century (*e.g.*, 1930s, 1980s) have occurred.

The issues are perhaps best put into perspective by examining the early settlement history of the region. While the factors driving homesteaders were mainly political and economic, the time of settlement (*ca.* the 1890s through the 1910s) featured climatic conditions that were generally conducive for agriculture. The droughts of the 1920s and 1930s, which were far more severe than any previously experienced, ended this run of favorable climatic conditions and precipitated social, economic and environmental upheaval. Much was learned from that experience and improved land management, tillage and other soil conservation practices have resulted in modern agriculture being far better adapted to climatic variability. This was evidenced by the relatively smaller impacts of the 1980s' drought, despite it being of similar severity to that of the 1930s. While this provides reason for optimism, it must be recognized that the paleoenvironmental record contains abundant evidence that even more severe droughts have occurred in the past. As a result, the most basic conclusion of this research is that management strategies based upon historic climate trends will prove inadequate, simply because the brief duration of the historic record does not encompass the full range of climatic variability.

Impacts

Paleoenvironmental research provides important insights into the response of geological and biological systems to climatic variability and change. Although this research can identify past analogues for many climate scenarios, evaluation of future impacts is still wrought with uncertainties owing to an inability to predict confidently the course of climate change. Within the Palliser Triangle, seasonality is likely to be far more important than annual means. For example, if greatest warming occurs during winter and is accompanied by increased snowfall, the impacts of a drier growing season could be partly mitigated. Furthermore, since

70% of the waters flowing through the Palliser Triangle are derived from the Rocky Mountains and foothills to the west (Campbell, in press), changes in snowfall, melt and glacier mass balance in these regions will exert potentially significant impacts throughout much of the southern prairies in terms of water for irrigation, recreation and consumption.

Given the uncertainties associated with climate prediction, many global change impact researchers advocate a "scenario-consequence" approach (*e.g.*, Harwell, 1993) that allows recognition of key vulnerabilities to establish priorities for managers and policy makers. The advantage that paleoenvironmental research brings to this approach is that it documents both the climatic "scenario" and the associated consequences (impacts). In other words, it reflects what has happened in the past, not what models project might happen in the future. Much of the economy of the Palliser Triangle is dependent upon the availability of water and soil, both of which have been significantly affected by past climate change. As a result, land use management must view these as dynamic, rather than static, resources. Ultimately, however, the greatest determinant of regional sustainability will be human responses to climate change. Integrating our understanding of hydrologic and landscape responses to past climate change with land use management strategies allows for a proactive approach to the mitigation of climate impacts, and facilitates development of policy alternatives that can be implemented once the course of future climate change is clear.

Future Research

The Palliser Triangle Global Change Project is the first systematic attempt to elucidate the Holocene paleoenvironmental record of the Canadian prairie grasslands. Previous studies were restricted to a very few sites, with interpretations largely based upon single proxy indicators. The Project has succeeded in developing an extensive array of data encompassing multiple proxy records from across the entire region. In addition, records of past climate change and associated landscape response provide the basis for spatial analysis of landscape sensitivity (*e.g.*, Sauchyn, 1996), in which areas most vulnerable to climatic impacts can be identified for strategic land use management.

Although Project data are still being analyzed and interpreted, it is possible to highlight a number of priorities for future

paleoenvironmental research. These are:

1) Recognition of extreme events. Climate variability is defined as much by the magnitude of extreme events as by shifts in mean climatic conditions. Presently, extended drought is the most readily recognized extreme event in the regional paleoenvironmental record. Documenting the frequency and magnitude of past extreme events is also important in terms of landscape response, where events such as flooding and dust storms can seriously affect residents of the region.

2) Quantification of past climate parameters. Characterization of past climates remains largely qualitative, with periods of greater aridity indicated by, for example, regionally depressed water tables or greater sand dune activity. Quantitative estimates of both paleolimnological and climatic parameters have been derived using transfer functions for some biological indicators (e.g., pollen, diatoms, ostracodes). Additionally, hydrochemical models provide potential for quantifying past climate on the basis of sediment mineralogy. Such approaches help facilitate the integration of proxy and instrumental climate records.

3) Increased temporal resolution. Chronological control for paleoenvironmental reconstructions from lake sediments is based largely on AMS ¹⁴C dating, generally providing century to, at best, decadal scale resolution. Nonetheless the finely laminated sediments present in some lakes offer potential for much finer (sub-annual) resolution, providing that the temporal significance of laminae can be determined confidently. Such reconstructions could provide critical information on the seasonal variability of climatic parameters. Limited chronological control also remains a fundamental obstacle to correlating evidence of past landscape response with possible climatic causes.

4) Analysis of spatial variability. Droughts of the past century have been highly variable in geographic extent. Integration of paleoenvironmental records, including landscape response, from across the region has the potential to document the spatial variability of past drought intervals, as well as to identify areas most susceptible to drought. Such work is critical to evaluate the appropriateness of extrapolating across large regions on the basis of data from a single site, as has commonly been done in the past.

5) Groundwater dynamics. The considerable efforts of provincial, federal and university researchers over the past three

decades have resulted in the Canadian prairies being one of the better studied areas in the world in terms of regional hydrogeology. Nonetheless, ground water is a critical component of the regional hydrologic system and traditionally is undervalued as a resource. Additional information on the extent, quality, residence time and recharge rate for aquifers over large areas of the prairies is still required. These data are not only critical for resource management, but also of fundamental importance for paleolimnological interpretations, where the significance of ground water is often recognized but an understanding of the associated hydrologic dynamics is generally lacking.

6) Monitoring. Although the paleoenvironmental record provides the context necessary for the evaluation of recent and future trends, enhanced monitoring programs are required to document such trends. Monitoring water resources and geomorphic processes not only provides an 'early warning' of resource depletion (Vance and Wolfe, 1996), but also helps to refine paleoenvironmental interpretations by documenting system response to measured climatic or other variables. Monitoring studies initiated as part of the Palliser Triangle Global Change Project (ground water, surface water chemistry, aquatic plant collection, sand dune activity) should be continued as part of regional monitoring initiatives.

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