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Since 1996, a broad range of publications has been produced by Canadian geomorphologists and hydrologists. These publications have been distributed in journals with national and international circulations. Although there remains a major focus on the study of observable processes in fluvial, aeolian, coastal and slope environments there is also a strong, historical component to explanations of landform, landform assemblages and sedimentary sequences. Some of these histories have incorporated the effects of high-magnitude (catastrophic) events, some of which may have no modern analogues. Perspectives on the interactions among microclimatic variables, including changes induced by human actions, continue to evolve. Forest clearance and its effects on evaporation rates, water-table levels and timing of snowmelt, the human use of wetlands and release of methane and carbon dioxide, will continue to demand the attention of scholars interested in explaining future climatic scenarios.


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A review of the research publications of physical geographers in Canada since 1996 is a challenging task because of the need to capture the breadth of research that has been done while conceding to an unavoidable selectivity necessary in obtaining a balanced cross-section of publications. The selected publications range in geographical scale from continental to local. Some describe research done at elevations that are among the highest in the world whereas others were conducted at or close to base level. Approaches to investigations are mostly those of field-oriented researchers, in some cases bolstered by experimental study of the more intractable aspects of field questions. Computational methods, especially surface fitting and GIS, have been adopted in handling large databases. The geographical distribution of field projects provides a window to the physical geography of Canada as well as other regions of like terrain. Adding to this diversity in geography is a range of perspectives in time, from the tens of thousands of years inherent in Quaternary histories to the minutes and seconds of hydraulic and aerodynamic fluxes. Still others struggle with the formidable task of projecting future scenarios of change from recent and current environmental observations. Although the present review is intended to highlight the contributions of geographers to progress in geomorphology and hydrology, the authors have included reference to some research from non-geographers to put the results from geographers into context. Nor have references been restricted to work done only in Canada. Where Canadian physical geographers have done research outside Canada, this review has been cited in the belief that the work has contributed to a pool of research with broad, global appeal.

Developments in Geomorphology

Studies of process mechanics

Research contributions on the mechanics of fluvial, aeolian and coastal processes continue to come from Canadian geomorphologists based in geography departments. LaPointe (1996) studied turbulent suspension of sediment in a sand-bed river, concluding that the dominant sizes of eddies associated with suspended particle mixing are one to five times the depth of water. Also highlighted was the effect of bursting which, though short-lived, did 20–90 percent of the work required in suspension. Robert et al. (1996) observed that clast protuberances have a dominant influence on the generation of turbulence on a gravel bed. Robert (1997) investigated velocity profiles along riffle-pool sequences and found that near-bed velocity gradients, and hence bed shear stresses, were higher over riffles at low flows. Spatially averaged shear stresses were 60.2 dyn cm$^2$ and 24.2 dyn cm$^2$ over riffles and pools respectively. At larger discharges the difference in bed shear was less pronounced. De Serres et al. (1999) deployed an array of electromagnetic current meters to observe the three-dimensional structure of flow at the confluence of two channels. Kostaschuk and Villard (1996) also reported on turbulence, or rather the absence of it, from subaqueous dunes in the Fraser River. Describing two types of large dunes, symmetrical and asymmetrical, they found no evidence of flow separation to the lee of symmetrical dunes. The symmetry of stoss and lee sides they explained by high transport rates averaging 0.073 kg m$^{-3}$ sec$^{-1}$ for near-bed/bed transport and 8.461 kg m$^{-2}$ sec$^{-1}$ for suspended bed-material load which was deposited on lee-side slopes of <8 degrees. Field instrumentation of dunes was not confined to dunes of subaqueous origin, but was applied to aerodynamic processes associated with reversing dunes in Nevada (McKenna Neuman et al. 1997). Using an array of 27 cup anemometers installed 0.3 m above ground along a transect over two reversing dunes, these authors concluded that better models are needed to predict the evolution of dunes over time intervals that typically are longer than the intervals being used in field research. Progress in this area will be of assistance to those interpreting the wind regimes of dunes and the combined effects of climate and land use on reactivation (Wolfe and David 1997; Sauchyn and Beaudoin 1998). Of special relevance here is the initiative by the Geological Survey of Canada to promote a multi-disciplinary approach to understanding the effects of past climatic regimes on geomorphic processes in Palliser's Triangle area of southern Alberta, Saskatchewan and Manitoba (Vance 1997). McKenna Neuman (1998) has done wind tunnel experiments on deflation lags comprised of pebbles of different sizes, shapes and spacing. After a turbulent boundary layer was induced and an upwind sediment supply introduced, the closely packed surfaces changed little, but as spacing increased the surface infilled with sand. Implications were discussed with respect to the partitioning of shear between particle motion and elements of surface roughness. Studies of surface roughness in rivers, formerly concentrated on
sand-bed rivers, have been extended to investigations of gravel-bed forms or structures (Church et al. 1998) and to particle size variations (Rice and Church 1998). Understanding the variability of fluid speeds, particle sizes and suspended sediment concentrations has important ecological application to the maintenance of fish habitat and fish populations (Beebe 1996). Very detailed studies of hydraulics and coarse-particle transport have also been in rock-bed channels, recently with respect to the particular condition of critical flow (Tinkler 1997). Studies of erosion and transport of sand-size (and finer) particles continue in nearshore coastal studies (Van Proosdij et al. 1999) and, like the extension of thinking to coarse-particle transport and bedrock erosion in fluvial research, there has also been in coastal studies a parallel attention given to the processes and forms of bedrock coasts (Trenhaile et al. 1998, Dubois et Nadeau 1999).

Transport data from rivers

As a result of the installation of gauging stations by government agencies and collection of fluid and sediment (mostly suspended) data, it has become possible to estimate the specific suspended sediment yields (in \( t \ km^2 \ a^1 \)) from different drainage basins. Research using these data predate 1996, but the increased availability of computer mapping routines and of more data have made it possible to sustain the momentum in this area of research. Stone and Sauderson (1996) reported yields from about 100 \( t \ km^2 \ a^1 \), to more than 500 \( t \ km^2 \ a^1 \) from Ontario river basins. Conrad and Sauderson (1999) reported a range of \( \sim 1-3000 \ t \ km^2 \ a^1 \) for basins in eastern Canada and the United States. Mapped patterns show that it is misleading to assume that only big rivers do significant work on landmasses. Work done per unit of contributing area is just as large in small basins as in large. In southern and central Ontario, the availability of weak, unconsolidated materials of Quaternary age explains many of the high values. Soft, glaciolacustrine clays underlie the channels draining into Lake St. Clair, explaining yields of 68 and 100 \( t \ km^2 \ a^1 \) whereas hard, Precambrian rocks occur beneath rivers flowing into Lake Superior and have yields as low as 5 \( t \ km^2 \ a^1 \). Pockets of higher yields have been found from some rivers flowing into Lake Superior and Lake Huron, but they correlate with the presence of raised, glaciolacustrine sediments.

De Boer and Crosby (1996) have cautioned against obtaining spurious correlations of specific sediment yield (\( Mg \ km^2 \ a^1 \)) and drainage basin area (\( km^2 \)) because both quantities contain the same term, namely basin area. Instead, they have recommended correlation of sediment yield (\( Mg \ a^1 \)) with basin area and further inspection of the numerical value of the exponent in the relationship. Church et al. (1999) have found a downstream increase in specific sediment yields in many Canadian rivers, concluding that most of the sediment in transport is derived from the river channels rather than from the more distant regions of drainage basins. Aiding the evaluation of the thickness of alluvial sequences has been the field implementation of ground-penetrating radar (LeClerc and Hickin 1997). Descriptions of the physical attributes of fluvial deposits have also been changing in that the shape of suspended sediment particles, an important correlate of contaminant transport, is now viewed as having fractal rather than integer dimensions and that these fractals change in space and time during transport (De Boer 1997a, De Boer and Stone 1998). Though not specifically related to clast morphology, Stooke (1998) has suggested novel ways of viewing the shapes of irregular objects using cartographic principles, a perspective that has potential for developing new descriptors of mineral and rock fragments in sedimentology.

The total tonnage of sediment discharged over known time can be used to estimate the mass \( (m_o) \) of rock and soil eroded per unit of time. Elevations interpolated from a surface fitting routine enable one to estimate the mass \( (m_t = \sum_{i=1}^{n} (\rho \times a_i \times \Delta h_i)) \) of rock stored in terrain, where \( \rho \) is average rock density, \( a_i \) is an elemental area on the surface, \( \Delta h_i \) is each interpolated elevation above datum and \( n \) is the number of elevations. The simple mass ratio \( (m_o/m_t) \) is then an estimate of the rate of erosion. One estimate for removal of the computed mass of North America above sea level was about 200 million years (Sauderson 1999).

Human – environmental interactions

Among the factors affecting fluvial erosion and sediment loads, the effects of human land use have become just as important as non-human factors. De Boer (1997b) was able to separate from lake sediment cores those layers which predated European settlement on the Canadian Prairies and those postdating settlement, concluding that the erosional response of Stony Creek basin (Saskatchewan) was more related to land use changes than to climatic variability. Land
use and seasonal pattern of precipitation were deduced to influence reservoir sedimentation in a monsoon climate (Ross and Gilbert 1999), with sediment delivery in the wet season two orders of magnitude higher than in the dry season. Rates of sedimentation ranged from 23.5 mm a\(^{-1}\) to 1 m a\(^{-1}\) in the deltaic region of the reservoir. Life of the reservoir was estimated to be 360 years. Contrasting is the relatively low rate of < 1 mm a\(^{-1}\) in glacially fed Chilko Lake (Desloges and Gilbert 1998).

The interval 1996-1997 highlighted the fragile nature of human occupancy of floodplains. Details of the hydrology and damages from the North Dakota – Manitoba flood of 1997 are still being evaluated, and a joint initiative between the Geological Survey of Canada and Manitoba Mines is looking at the flood history of the region (Thorleifson et al. 1998). Scientific evaluation of the Saguenay flood of 1996 have been published. Brooks and Lawrence (1998) have provided a photographic record of the effects of the Saguenay flood and their description of the meteorological and hydrological conditions remind one of the difficulties in predicting the behaviour of rivers. Discharge peaks of 653 m\(^{3}\) sec\(^{-1}\) on the aux Sables river and 1100 m\(^{3}\) sec\(^{-1}\) on the Chicoutimi were the largest ever measured on these rivers, exceeding the capacity of dams which were overtopped by floodwaters. Flood frequencies remain extremely complex to forecast, and mathematical analysis continues using a number of methods, most recently L-moments (Glaives and Waylen 1997). The importance of understanding the nature of human and environmental interactions has been highlighted recently in a feature issue of The Canadian Geographer edited by Jacobs and Bell (1998), in which authors deal with a range of issues ranging from dendrochronology of climate (Luckman 1998a) to coastal submergence (Shaw et al. 1998) and the fragility of dry regions (Sauchyn and Beaudoin 1998).

Computational mapping and geomorphology

Numerical mapping has been adopted as a common tool to show spatial patterns of geomorphic data. From an array of surface fitting methods, some statistical and some exact, the multiquadratic method (Hardy 1971) has been the most versatile in its applications to terrain science. The equations are reproduced here to show this versatility. In the form

\[ \sum_{j=1}^{n} c_j \left[ (x_i - x_j)^2 + (y_i - y_j)^2 \right]^{p/2} = z_i \]

(1)

the basis function is that of a right-circular cone (the quadric), the \(x_i\) and \(y_i\) are the coordinates (longitudes and latitudes) of sampled sites and the \(z_i\) are sampled scalar data, in application, specific sediment yields (Stone and Saunderson 1996, Conrad and Saunderson 1999) and terrain elevations (Saunderson 1999). The only unknown in the equation is the solution vector of coefficients, \(c_j\), which is obtainable from one of a number of methods available for solving systems of simultaneous linear equations. Interpolated values, \(z_p\), may then be obtained at any number of locations inside the sample space using

\[ \sum_{j=1}^{n} c_j (x_p - x_j)^2 + (y_p - y_j)^2 \right]^{p/2} = z_p \]

(2)

where \(x_p, y_p\) are the coordinates of the interpolated values. Removal of one coordinate from the left-hand side changes the dependency of a surface fitting routine to one of curve fitting, whereas addition of a third coordinate transforms it to a three-dimensional method. Thus, a physical geographer might use the equations to (1) fit topographic profiles (elevation as a function of distance), (2) fit terrain surfaces (elevation as a function of latitude and longitude) or (3) fit three-dimensional surfaces (perhaps air temperature as a function of latitude, longitude and elevation).

Software now widely available for GIS has been applied to geomorphic problems. Rowbotham and Dudycha (1998) produced a regional mapping of slope stabilities in the Phewa Tal area of Nepal using data obtained from existing maps and aerial photographs. They generated terrain units which were either stable or unstable and which correlated very closely to slope stability maps produced by more conventional means. More general application of such mapping methods in alpine areas would be very timely, given the observation by Hewitt (1998) from research in the Karakoram Himalaya that of 115 rockslides or rock avalanches mapped, at least 73 had formerly dammed tributaries to the Indus and influenced drainage evolution for most of Holocene time.

**Progress in Glacial Geomorphology**

The glacial heritage of the Canadian landscape continues to captivate the attention of many researchers. Between 1996 and 1999, over 265 papers were published which dealt specifically with the glacial geomorphology of the Canadian landscape. Of these publications, the majority focus on either Late
Quaternary ice sheet dynamics (45%), delineation of the surficial geology of glaciated landscapes (20%) or on till sedimentology (13%). Interest in the origin and development of specific glacial landforms is limited (14%) and heavily weighted by the Oak Ridges Moraine (ORM) Project (Pugin et al. 1996). While the findings of this research have been presented in a number of publications with international appeal (e.g. Boreas, Geology, Bulletin of the Geological Society of America), the Canadian Journal of Earth Sciences, Géographie physique et Quaternaire and publications released by the Geological Survey of Canada provide the most important national venues.

Ice sheet dynamics

An understanding of the late-Quaternary history of the Canadian landscape remains incomplete. In the Canadian Arctic, research on Ellesmere Island (Aitken and Bell 1998; Bell 1996; Blake 1999; England 1996, 1997, 1999; Gualtieri and England 1998; O’Cofaigh 1998; Zreda et al. 1999), Axel Heiberg Island (Aitken and Bell 1998; Bednarški 1998) and Bathurst Island (Bednarški 1996) has focused on glacial and glaciomarine sediments in an effort to understand the regional glacial dynamics of this period. On Devon Island, Dyke (1998, 1999) examined Holocene delevelling following the last glacial maximum and considered the implications for Inuitian Ice Sheet geometry. Studies in the vicinity of Baffin Island have considered the seafloor (Blake Jr. et al. 1996) and surface evidence (Dredge 1999; Hodgson 1997) for glaciation. Similar studies of the lithological composition and carbonate contents in tilts, glacial striations and the glacial geomorphology have allowed for the identification ice flows at the northeast end of the Ungava Peninsula (Brunée and Gray 1997) and in the Kivalliq region, Nunavut (McMartin and Henderson 1999). Along the western edge of Canada researchers have reviewed the evidence indicating that late-Quaternary glaciers spilled from the Coast Mountains into the Pacific (Barrie and Conway 1999). It is now apparent that in the Fraser Valley area of southwestern British Columbia, the Cordilleran ice sheet readvanced on at least two occasions near the end of the last glaciation (Cglague et al. 1997; Gbellault et al. 1997). Nevertheless, there is growing evidence suggesting that some coastal sites remained ice free during the last glaciation (Barrie and Conway 1999, Howes 1997).

Recent investigations within the Canadian cordillera have been enhanced by government programs concerned with drift exploration (Bobrowsky et al. 1996). In the northern cordillera, Catto (1996) and Catto et al. (1996) examined the northern portal of the postulated Ice-Free Corridor and the character of Laurentide, Cordilleran, and Montane glaciation in the western Peace River. Dewez and Geurts (1996) considered ice flow patterns in the Ruby Range and Duk-Rodkin et al. (1996) reviewed the Late Tertiary to late Quaternary record in the Mackenzie Mountains. In the Taseko Lakes area, British Columbia, Huntley and Broster (1997) demonstrated that a four phase model was necessary to explain the late Wisconsinan Fraser Glaciation retreat-phase deposits and landforms they discovered. Huscroft and Plouffe (1999) describe Glacial Lake Knewstubb in the upper Nechako River drainage basin of central British Columbia, formed during the Late Pleistocene by the impoundment of glacial meltwater. Further to the south, Dixon-Warren et al. (1997) described glacial deposits northeast of Kamloops and Vanderburgh and Roberts (1996) documented the character of proximal glacial deposits from their seismic stratigraphy in the north Okanagan Valley.

The interaction of Cordilleran and Laurentide glaciers east of the Canadian Rocky Mountains remains a focus of investigation (Fisher 1999). Leveson and Rutter (1996) suggest that Late Wisconsinan glaciers flowing from the mountains coalesced with Laurentide glaciers and were deflected southeasterly along the mountain front. Holme et al. (1998) examined exposures along the Castle River valley and recorded evidence for an oscillating montane ice front. Jackson et al. (1996, 1997) support the views that the Laurentide Ice Sheet was the most extensive of Pleistocene ice sheets in the Alberta Foothills. Mandryk (1996) has emphasized that during the late Wisconsinan many areas of Alberta were dominated by chaotic ice stagnation conditions. Recent findings by Bednarški (1999) were used to summarize the Quaternary history of a broad area of northeastern Alberta.

Glacial Lake Agassiz was the largest of the many proglacial lakes formed as continental drainage was impounded against the retreating Laurentide ice margin in Saskatchewan and Manitoba (Mann et al. 1999). Investigations into the history of the lake continue (Rack et al. 1998; Tackman et al. 1998) and are providing clues as to its possible drainage into Mackenzie basin via the Clearwater River, Saskatchewan, 9900 years ago (Fisher and Souch 1998; Rempel and Smith 1998).
In northern Ontario and Quebec, the general chronology of ice retreat has been substantiated by Morris (1998), Paradis et Bolduc (1999), Veillette (1996, 1997) and Veillette et al. (1999). Mooers and Lehr (1997) have shown that the western Lake Superior region records a complex sequence of late Wisconsinan ice advances and retreats of the Laurentide Ice Sheet from accumulation centers in Quebec and Hudson Bay. In southeastern Quebec, along the St. Lawrence River Valley and in the Gaspé Peninsula, late glacial sedimentary sequences have provided significant regional deglaciation insights (Clet et Occhietti 1996; Dionne 1998; Dionne and Occhietti 1996; Hetu 1998; Occhietti et al. 1996; Parent and Occhietti 1999; Richard et al. 1997).

Late Wisconsinan glaciation and sea level activity in the Maritime region of eastern Canada has been summarized by Stea et al. (1998). While Broster et al. (1997) confirmed the dominant ice-flow directions in the Waterford area, New Brunswick, Catto (1998a) used glacial stratigraphy in the Malpeque-Bedque region, Prince Edward Island, to indicate initial eastward ice flow, followed by a second glacial event with flow towards the south and southwest in the Gulf of St. Lawrence. Strumpf et al. (1997) analyzed dispersal patterns for till clasts and matrix geochemistry in southwestern New Brunswick, and used this information to define the dominant glacial transport direction in an area of ice-flow complexity. In Nova Scotia, McClanahan and DiLabio (1996) described the ice-flow history of southeastern Cape Breton Island and Stea and Mott (1998) developed a deglaciation model from a chronology of glacial lake sediments. The Quaternary geomorphology of Newfoundland was examined in the Buchans area by Klassen and Murton (1996) and on the Avalon Peninsula by Catto (1998b) and MacPherson (1996).

The eastern and northeastern offshore margins of Canada have yielded new insights into Late Pleistocene events (Andrews et al. 1998; Hulbe 1997). The final collapse of the Laurentide Ice Sheet and the release of a massive meltwater pulse is known to be a key element in the history of ice sheet/ocean interactions (Clark et al. 1996; Kirby and Andrews 1999; Matsumoto 1997), with Heinrich events precipitating iceberg deposited detrital carbonate throughout the North Atlantic (Andrews et al. 1996; Andrews et al. 1998; Andrews et al. 1999; Bischof et al. 1996; Hesse and Khodabakhsh 1998; Hesse et al. 1999; Kerwin 1996). While Hunt and Malin (1998) have suggested the possibility that the Heinrich events were precipitated by ice-load-induced earthquakes, Veiga-Pires and Hillaire-Marcel (1999) note that the duration and sequence of events recorded by the Heinrich layers are still poorly constrained. Nevertheless, the extent of their influence is widespread along the eastern Canadian seaboard. Investigations on the inner shelf off Newfoundland (Shaw and Courtney 1997; Shaw et al. 1999) and on the Scotian Shelf (King 1996; Piper and Skene 1998) have revealed post-glacial sediments believed associated with the Heinrich events.

Terrestrial records of Late Wisconsinan meltwater events also appear to suggest that deglaciation was accompanied by catastrophic drainage of meltwater stored at the base of the Laurentide ice sheet (Shaw 1996; Shaw et al. 1996; Shoemaker 1999). Kor and Cowell (1998) examined sculptured bedrock on the Bruce Peninsula, Ontario, and showed it to be the consequence of subglacial meltwater sheetflood events. Similar landform evidence of catastrophic flooding was recorded in Alberta by Munro-Stasiuk (1999) and in southern British Columbia by Shaw et al. (1999).

Holocene glaciation

Comparatively little attention has been paid to glacial activity within the Holocene interval (Osborn and Geryo 1997). Clague and Mathewes (1996) provided insights into the Neoglacial history of the northern Coast Mountains of British Columbia, and Smith and Laroque (1996) provided the first calendar-dating of a Little Ice Age glacier advance on Vancouver Island. Within the Canadian Rocky Mountains, Dirszowski and Desloge (1997) and Luckman (1996) have furthered our understanding of Little Ice Age dynamics. Although many studies report a recent loss of glacier ice mass within the Canadian cordillera (Lawby et al. 1995), Cogley et al. (1996) did not find such a trend for White Glacier in the High Arctic. If climatic warming has taken place at high latitudes, the findings for White Glacier are not supportive, and this is contrary to the common wisdom that the Arctic amplifies the climatic change signals. For large glaciers, mass balance studies suffer from inadequate spatial coverage data for snow accumulation and ice ablation though remote sensing may improve the mapping of the snow and radiation components (Gratton et al. 1994, Adam et al. 1997).

The drainage of glacier meltwater was studied in Alberta (Smith 1995) and in northwestern British Columbia and Yukon, where Smart (1996) studied the subglacial route in temperate glaciers. The ice has a

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hydraulic conductivity several orders larger than that of the till below the glacier (Stone and Clarke 1996) and is likely to be preferential for meltwater flow.

Glacial landforms

Landscape-scale geomorphic features distinguish vast areas of Canada and have been the focus of several investigations. In eastern Québec, Brennand et al. (1996) and Brennand and Shaw (1996) describe the origin of the massive Haricana complex. Recognized as a subglacial landform formed by meltwater outburst floods, the complex may be genetically linked to palimpsest glacial landform systems in Labrador (Clark 1999). In southern Ontario, the Geological Survey of Canada and the Ontario Geological Survey are involved in a multi-year research program designed to understand the complex landform-sediment geometries and event sequences of the Oak Ridges Moraine (Barnett et al. 1998). The moraine is a major physiographic feature and is made up of a number of depositional elements (Paterson and Cheel 1997; Russell et al. 1998). Gilbert (1997) examined the glaciolacustrine part and proposed that a glacial lake was dammed on the Oak Ridges Moraine between the retreating Simcoe and Ontario lobes and the Niagara Escarpment to the west. Pugin et al. (1996) and Pugin et al. (1999) conducted a regional seismic reflection survey and found that tunnel channels in glacial sediments characterize sections of the moraine.


Landforms and features resulting from glaciotectonic activity appear to be widespread. Christiansen and Sauer (1997) examined the Dirt Hills ice-thrust feature in southern Saskatchewan, proposing it developed as Laurentide ice readvanced up the Missouri Coteau escarpment and stacked subglacial slabs of bedrock and drift. An interpretation of the acoustic architecture of this type of structure led Lonne and Syvitski (1997) to suggest they formed mainly during advances of the ice-front, with only thinner sediment packages emplaced during ice-front stillstand episodes. The influence of glaciotectonics on lake sediments in Kananaskis Country, Alberta, was described by Evans et al. (1999) and Park and Broster (1996) note the influence of glaciectonic fractures on wall failure in open excavations at the Heath Steele Mines, New Brunswick. In an interesting study, Anderson and Hinds (1997) note that the most recent phase of accelerated leaching in the Canadian prairies occurred during the Quaternary, probably as a result of glacial loading and unloading.

Detailed investigations of till deposits have led to the hypothesis that subglacial sediment deformation may provide a glaciological mechanism to explain the shape and volume of the Laurentide Ice Sheet (Clark et al. 1996; Eyles and Boyce 1998; Licciardi et al. 1998). The deforming bed debris-rich basal ice continuum also has implications for the formation of glacial landforms (flutes) and sediments (melt-out till) (Hart 1998). Other investigations of allochthonous sediment in till (Cogley et al. 1997), clastic intrusive sheets and dikes (Deimhanis and Rappol 1997), subglacial till fabrics and Bond cycles (Hicock et al. 1996, 1999) continue to emphasize the significance of basal entrainment, transport and deposition processes by the Laurentide Ice Sheet (e.g. Zdanowicz et al. 1996).

The application of new dating techniques improved our understanding of the timing and magnitude of glacial erosion and deposition. Cosmogenic Cl-36 exposure dating has been completed in the
eastern Canadian Arctic (Steig et al. 1998; Bierman et al. 1999; Davis et al. 1999) and southwestern Alberta (Jackson et al. 1997). Aspartic acid racemization was used to evaluate the marine Quaternary record (Goodfriend et al. 1996) and magnetostratigraphic dating has provided valuable insights into Early Pleistocene volcanism and glaciation in northwestern Canada (Barendregt et al. 1996; Jackson et al. 1996; Spooner et al. 1996; Barendregt and Irving 1998).

Progress in Periglacial Geomorphology

The periglacial regime of northern Canada covers a vast and diverse landscape, encompassing settings ranging from the arid terrain of the High Arctic to the high mountainscapes of Yukon. Between 1996 to 1999, more than 100 papers and two books were published that deal specifically with either permafrost and/or periglacial processes/landforms within Canada. Of these publications, the majority (57%) focus on permafrost and active layer dynamics in the Canadian north. Notable among these contributions are those contained in the proceedings of the Seventh International Permafrost Conference (49 papers) held in Yellowknife (Lewkowicz and Allard 1998) and recorded in the second edition of The Periglacial Environment (French 1996). While the journal Permafrost and Periglacial Processes remains the preferred forum for widespread dissemination of these findings (22 papers), the Canadian Journal of Earth Sciences (8 papers) and a host of other journals (e.g. Canadian Geotechnical Journal, Geografiska Annaler) provide a record of ongoing research activities in a variety of Canadian periglacial settings.

Permafrost and active layer processes

The geomorphology of the Canadian north is in many ways defined by permafrost and by the challenges of living with the seasonally thawed active layer (Wolfe 1998) in a changing landscape (Dallimore et al. 1996; Wolfe et al. 1998). In their attempt to better understand permafrost dynamics, researchers continue to evaluate its past (Allard et al. 1996; French 1998; Kuhry 1998; Wang and Evans 1997; Moorman et al. 1996; Moorman et al. 1998; Pollard and Bell 1998), present (Burn 1998a; Couture and Pollard 1998; French and Egorov 1998; Hodgson and Nixon 1998; Robinson and Pollard 1998; Wolfe 1998) and future (Burn 1998b) characteristics, using a variety of innovative techniques (Granberg and Vachon 1998; Leverington and Duguy 1997; Lewkowicz and Duguy 1999; Menard et al. 1997). Essential to these investigations are those focused on the active layer (Burn 1998c). Historical changes to the active layer are being monitored at numerous sites (e.g. Harris 1998a; Nixon and Taylor 1998), with attention being given to documenting the effects of heat flow on ground thaw (Carey and Woo 1998a; Hinkel et al. 1997). These appear to be critical arenas of research given the sensitivity of this setting to anthropogenic (Nolte et al. 1998; Seburn and Kershaw 1997) and zoological activity (Hall 1997).

Research on permafrost landforms, such as palsas (Horvath 1998) and pingos (Gurney and Worsley 1996), continues in the Canadian north. Growth data have been obtained for 11 pingos for periods ranging from 20 to 26 years (Mackay 1998), and seems to emphasize that sub-pingo water lenses are essential to pingo growth (Parameswaran and Mackay 1996).

Effect of frost action

Frequent temperature oscillations around the freezing point are essential to cryogenic activity in the periglacial zone, be it at high latitude (Mackay 1997) or altitude (Harris and Pedersen 1998). Researchers have noted the physical impact of associated frost shattering processes in Yukon (Lauriol et al. 1997), Northwest Territories (Murton 1996; Mackay 1999a) and in the Southern Canadian Rocky Mountains (Prick 1998).

In permafrost regions, researchers have described how seasonal thermal contraction under contemporary climatic regimes has resulted in the rapid development of ice wedges (Brent and Harrison 1998; Mackay 1999b). Exhumed sand wedges and ventifacts in the upper Churchill watershed of northwestern Saskatchewan (Fisher 1996) on Summer and Hadwen Islands, Western Arctic Canada, reflect even more severe environmental changes at the close of the last ice age. The development and maintenance of sorted and non-sorted patterned ground is dependent upon cryogenic mechanisms initiated by frost action (Washburn 1997), and research continues on Devon Island (Anderson and Bliss 1998) and at the top of Plateau Mountain, Alberta (Harris 1998b) to understand the various environmental relationships.

Slope processes in the Canadian periglacial zone range from those associated with the deep-seated creep of massive ice (Dallimore et al. 1996) to episodically-induced active layer detachment failures (Kokelj and Lewkowicz 1998). Nevertheless, recent contributions in this area are limited to those associ-
ated with solifluction and rock glacier studies. In the case of the former, Washburn (1999) reports the results of a long-term study (1981-1989) at Resolute Bay in the Canadian High Arctic of active solifluction (28mm a\(^{-1}\)). In an interesting experiment Foriero et al. (1998) attempted to simulate hillslope creep at a site in the Northwest Territories.

Rock glacier studies at three locations in the Canadian cordillera offer new insights into their behaviour and rheology. In Selwyn Mountains of the Yukon and Northwest Territories, Sloan and Dyke (1998) obtained 12-year average velocities for 15 rock glaciers (0.20 ± 0.11 m a\(^{-1}\)). In the nearby St. Elias Mountains, Johnson (1998) continued his long-term assessment of rock glacier morphology, aided by electrical resistivity measurements which provided insights into the geometry of the permafrost and the amount of ice in the sediments (Assier et al. 1997; Evin et al. 1997). Far to the south in the front ranges of the southern Canadian Rocky Mountains, Koning and Smith (1999) report on the results of an eight-year geodetic survey at King's Throne rock glacier where horizontal surface movements averaged 0.54 ± 0.04 m a\(^{-1}\).

**Progress in Hydrology**

In view of the northerly location of Canada, hydrological research has a continued cold region bias (French and Slaymaker 1993). During the past five years, researchers maintained their main thrust in hydrological process investigations, with strong emphases on the field component. Advances have been made in most aspects of hydrology and the cold-region process research for which Canadian contribution is recognized internationally.

Snow and ice

Over half of Canada has snow on the ground for at least six months and the snow cover often lasts ten months in the Arctic Islands and on the high Cordilleran mountains. For the high latitude and high altitude areas, the winter snow cover is intensely cold (-15°C) and seldom experiences mid-season melting. In the tundra environments, blowing snow conditions lead to redistribution of snow, producing large unevenness in the snow cover. Woo and Young (1998) noted that the snow distribution pattern can be inferred and mapped from the terrain, with the exposed hilltops having thin snow, the gullies and valleys infilled by large quantities of snow, flat ground collecting intermediate amounts, and local topographic convexities or concavities giving rise to intra-slope variabilities in the snow cover. In the prairies, tall wheat stubbles or rows of wheat grass can trap more snow than the short-stubble or alfalfa fields (McConkey et al. 1997, Steppuhn and Waddington 1996) and this influences soil moisture recharge in the spring, thus affecting crop yield. There is no apparent relationship between snow depth and the subdued topography of the prairies (Lapen and Martz 1996). Shook and Gray (1996) observed that the prairie snow distribution is fractal at a local (<30m length) scale, but becomes random when examined at scales beyond this limiting length of 30m.

Blowing snow is subject to sublimation. Pomeroy and Gray (1995) developed a model which estimates that a large portion of the prairie snow cover and one quarter of the tundra snowfall may be sublimated. In forested environments, the interception of snowfall by coniferous trees was studied by continuously weighing cut trees hung in the woodlands of central Saskatchewan and southern Yukon. Using the results from these experiments, Hedstrom and Pomeroy (1998) derived a method to estimate snow interception as a function of leaf area index, canopy cover-age, tree species, air temperature, wind speed, time since snowfall and the snow amount. They found that sublimation loss from the intercepted snow can be up to 5mm per day in the southern boreal forest.

Snowmelt

Downward percolation of meltwater in a snow cover, particularly for very cold snow, is highly variable over short distances (Marsh 1999). Preferential water movement along vertical flow fingers and horizontal planes between snow layers (Marsh and Pomeroy 1999), together with refreezing that forms ice columns and ice layers, complicates the flow pattern and delays the delivery of meltwater to the ground.

In open areas with uneven snow distribution, the snow cover breaks into patches after an initial melt period. Then, heat is advected from the bare ground to the snow. Neumann and Marsh (1998) showed that local advection increases the melt downwind of the leading edge of the snow patch, but the influence of this advection decreases exponentially with distance from the edge.

Tree canopies reduce the energy available to snowmelt within the forest. Metcalfe and Buttle (1998) found that the melt rate decreases exponen-
tially with the non-canopy (gap) fraction in a boreal forest. They noted that the snow at a dense black spruce site did not melt completely until 12 days after the snow disappeared from an open site. Forest type and disposition also influence melt. Carey and Woo (1998b) compared the melt in spruce open woodland on a north-facing subarctic slope with snowmelt in an aspen forest on a south-facing slope. Snowmelt was advanced by 10 days in the aspen forest.

Glaciers

Glacier research has retreated from its heydays of the 1970s but field data accumulated over the years, when rescued from discontinued programmes, allowed medium to long-term mass balance studies to be carried out and hence contributes valuable information to the climatic change debate. Runoff generated by the ablation of an Arctic glacier has been correlated with air temperature to provide a simple predictive tool (Wolfe and English 1995). Discharge from small glaciers has been found to be enhanced by glacier retreat (Hopkinson and Young 1998). This is unlikely to continue for small glaciers if they suffer large loss in the ice cover over the long term.

Ground frost and icing

Ground ice in the soil affects the infiltration of snow meltwater in the spring. An empirical equation (Granger et al., 1994) rates the infiltration into frozen soil as a function of the winter snow and the soil moisture in the fall. Harms and Chanasyk (1998) found it difficult to apply this empirical relationship to southern prairies, probably because of mid-winter melts which alter the snow cover and the surface soil moisture conditions. Zhao and Gray (1997) produced a more physically-based approach to include initial surface saturation, soil water and ice content, initial soil temperature and the duration of infiltration. This may improve the estimate of infiltration into frozen soils though it introduces more variables into the equation than the previous studies.

The discharge of groundwater in cold regions can produce icings as the water freezes. Hu and Pollard (1997a) noted that the river ice is first formed along the banks and then extends across the entire river. Ice then thickens by freezing of the stream water, by the inclusion of snow in the ice and by the formation of icing as overflow is frozen and incorporated in the river ice cover. Icing growth occurs over short distances from the source of water discharge and there is a constant shift in the position of the new icing added to the ice cover (Hu and Pollard 1997b). For small streams, icing melt contributes a small quantity to stream flow (Reedyk et al. 1995) but for large rivers such as the Firth in the Yukon, icing can constitute >30 percent of annual groundwater discharge which provides about half of the river flow (Clark and Lauriol 1997).

Slopes

Advances in slope hydrology in the past decades have improved our knowledge on the mechanism and patterns of runoff on temperate slopes (Anderson and Burt 1990). Much remained unknown on flow generation from slopes in high latitudes but there has been considerable progress in this regard during the past several years, from the Arctic to the temperate shield regions, from the scale of entire slopes to the flow mechanics within segments of the slopes.

Between-slope differences in hydrological characteristics reflect the influences of microclimate, vegetation and soil. In central Alberta, Harms and Chanasyk (1998) observed that the south slopes had earlier snowmelt, received more soil moisture in winter and yielded less runoff than the north slopes. Similarly, Carey and Woo (1998b) found that a south-facing slope (without permafrost) in subarctic Yukon had earlier snowmelt but yielded no runoff compared with its north-facing counterpart which is underlain by discontinuous permafrost. In the High Arctic, Young et al. (1997) found that the precipitation, snowmelt, frost table configuration, water table fluctuation and flow production were different among four slopes of different orientations. There, the contrasts in radiation, air and ground temperatures were also exaggerated during a warm, dry summer.

The mechanisms of slope runoff are different among slopes in different environments. In the Canadian Shield of central Ontario, Devito et al. (1996) found that there is continuous coupling of groundwater flow from the upland slopes, through the deep overburden, with the wetlands in the valleys. Where the overburden is shallow, however, the connection is decoupled after the snowmelt season, so that there is no detectable water table in the footslope area and the streams dry up in the summer (Hinton et al. 1998). In detail, saturation overland flow occurs in the upland zone only when the thin
overburden is completely saturated (Allan and Roulet 1994). Otherwise, subsurface flow occurs along the interface of the thin overburden and the bedrock (Peters et al. 1995), with water entering this interface zone through vertical macropores in the overburden. With thick overburden (up to 15 m), runoff occurs mainly as groundwater flow above the bedrock and is discharged at the footslope zones or at hillslope concavities.

In the subarctic, Carey and Woo (1999) did not observe runoff from the south-facing slope which only had seasonal frost. In contrast, the north-facing slope where a 0.5 m organic layer overlies boulder clay with permafrost, snowmelt generated flows which were conveyed downslope along rills and gullies, in soil pipes and as matrix flow in the organic layer. Groundwater flow in this shallow organic zone is orders of magnitude faster and larger in quantity than the flow in the deeper mineral soil. The presence of relatively impermeable permafrost prevents deep percolation and facilitates groundwater discharge to the lower slopes during the summer.

The distinction between fast flow in organic soils and slow flow in mineral soils applies also to the Low Arctic tundra with hummocky landform in a continuous permafrost environment (Quinton and Marsh 1998). The inter-hummock depressions, with widths from several centimetres to tens of centimetres, are mostly filled with organic materials with hydraulic conductivities that are several orders of magnitude larger than the mineral soils that underlie the hummocks. Preferential flow is channelled along these depressions, both as surface runoff and as subsurface flow in the organic zone.

In the largely barren, polar desert environment of the Arctic Islands, snowmelt runoff is the dominant period with slope flow as the frozen ground in the spring prevents infiltration to encourage overland flow. This mechanism is described by French (1996). Where late-lying snowbanks remain in slope depressions, their meltwater often saturates the zone below the snowbank to sustain overland flow for a protracted period. Subsurface flow may seep into zones where the frost table is deep or where the slope gradient is large (e.g. at slope convexities) and only subsurface flow, or no flow at all, may occur. At slope concavities, focussed exfiltration of groundwater can again generate surface runoff (Woo and Xia 1997). Consequently, slopes in the polar desert may show alternating zones with and without surface runoff, as dictated by the relative magnitudes of infiltration and exfiltration.

Slope hydrology is important to the timing, magnitude and duration of streamflow production. On slopes where vertical processes (rainfall, snowmelt, infiltration and evaporation) dominate, little water is available for lateral flow and the contribution of meltwater and rainwater to the rivers will be negligible (e.g. the subarctic south slopes described by Carey and Woo 1999). On the other hand, where lateral runoff is significant, as is found on many slopes with shallow permafrost or with impervious shield bedrock, fast snowmelt or heavy rain can generate much slope runoff to reach the streams. In mountainous terrain, synchronous occurrence of snowmelt in various elevation bands and vegetation zones can yield large runoff simultaneously at different parts of the slope and this can cause very high peakflow in the streams (Janowicz et al. 1997).

Forests

Forests cover over 40 percent of Canada and they significantly affect hydrology through modifying the distribution of precipitation, the snowmelt processes, evaporation and runoff. The interception of snow by trees and its subsequent sublimation is presented in the 'snow and ice' section. Rainfall interception in a boreal forest environment includes the catch by the spruce canopy and by the moss cover on the forest floor (Price et al. 1997). Like a hardwood forest in southern Ontario (Carlyle-Moses and Price 1999), most of the rainfall caught by the vegetation is evaporated during or soon after the rainfall event.

Evaporation from the boreal forests of central Saskatchewan and northern Manitoba received the research attention of a major project in 1995-98, known as BOREAS (Boreal Ecosystem-Atmosphere Study), using data collected from meteorological towers, low-flying aircraft and satellite-platform remote sensing. Aircraft measurements of evaporative flux agreed with flux calculations from the tower data. Evapotranspiration at these BOREAS sites was lower than expected previously. The low seasonal evapotranspiration rates are attributed to the frozen condition of the tree root system in the spring and the low photosynthetic rates in mid-summer that reduce the stomatal conductance. Most results of BOREAS are reported in a special issue of the Journal of Geophysical Research (Sellers 1997). In comparison with these boreal forests, Lafleur and Rouse (1995) reported that evaporation from the forest at Churchill, Manitoba, was lower than that at a tundra
site. Lafleur et al. (1998) noted that the evaporation from an eastern Ontario deciduous forest was larger than that from a mixed forest site.

Removal of trees by logging reduces evaporation and advances the timing of snowmelt, though the loss of interception is reduced (Meng et al. 1995). As a result of reduced water loss to evaporation, the cutting of trees in forested wetlands in the St. Lawrence Lowlands was followed by a rise in the water table (Dubé et al. 1995).

Lakes and wetlands

Despite the presence of several large lakes in northern Canada, there has been little research on their hydrological behaviour. Since 1997, evaporation and the lake ice regime of Great Slave Lake were studied. For 1997, annual lake evaporation fell within the 300-400 mm range expected of the 60-65°N latitude. As the end of the 1997-98 El Niño year, however, lake ice was thinner than normal so that the break-up date was advanced by several weeks, and the freeze-up was not completed until January 8, 1999. This greatly extended the open water period and lake evaporation reached 500 mm (Rouse in press).

About 14 percent of Canada is covered by wetlands. Recent research has improved knowledge of their hydrological responses to natural processes and to human activities, as well as their roles in carbon and methane fluxes. The relationship between many wetlands and their adjacent upland areas has been examined, from the arctic patchy wetlands (Woo and Young 1998), to the subarctic patterned wetland (Quinton and Roulet 1998) and peatland in headwater areas of the Canadian shield (Brancifireun and Roulet 1998). Runoff responds quickly to meltwater input, indicating a limited storage capacity of the wetlands in the spring to accommodate the rapid release of meltwater and to attenuate fast flows (Devito et al. 1996; Glenn and Woo 1997). In the dry period, evaporation losses, sometimes accompanied by a severance of flow connection with their adjacent uplands, lead to a drop in the water level. However, the presence of a moss and lichen cover, commonly found in wetlands, can retard evaporation as these non-vascular plants are ineffective in bringing water to the surface other than through capillary suction (Campbell and Williamson 1997).

Human activities in wetlands can alter the hydrology significantly. One notable impact is due to the harvesting of peat in wetlands (Price 1996, 1997). Peat mining and drainage alter the normally high water table status and desiccate the surface zone of the wetlands. Restoration of these harvested areas is the subject of active research (LaRose et al. 1997).

Water table fluctuations affect the aerobic-anaerobic status of wetlands. When extensive wetlands are flooded, decomposition of organic matter is retarded and methane is produced from large areas. Conversely, in a hot dry summer, low water tables allow the wetlands to become a source of carbon dioxide as the peat decomposes (Lafleur et al. 1997). Given the large areal coverage of many Canadian wetlands, the release of such greenhouse gases as methane and carbon dioxide has significant implications on the climate.

Concluding Remarks

The momentum already gained by researchers from Canada on process mechanics in geomorphology has continued to yield publications with national and international dissemination. On just about all fronts the results from a diverse range of activities have contributed to the global pool of information on fluvial, aeolian, coastal and slope processes. Some of this work is distinctive enough to give Canadian geomorphology considerable recognition internationally. Some will also, no doubt, be controversial – as is some already. Still incomplete are the logical connections among the varied scales (and durations) of mechanical action and the geometrical attributes of terrain form. Perhaps a renewed interest in ‘action’, the product of force and time, will result in a more refined blend of process and form interactions through time.

As we move into a new millennium, hydrological research in Canada undergoes major transitions. Automated data gathering, together with gradual erosion of the government data collection programme and shrinkage of the climatological and hydrometric networks, are changing the pace, nature, amount and spatial coverage of data acquisition. Coupled with software development, there is a shift in the processing, analysis and presentation of hydrological information, liberating the researchers from the tedium of data entry and manipulation, but demanding the discerning hydrological insight and experience to ensure that subtle errors in the data do not escape unnoticed. With increasing computer power and the ease of applying models to hydrological problems, many young hydrologists are enticed into the comfort of modelling research, sometimes at the expense...
of rigorous, expensive and time-consuming field work. Field research in high latitudes and high altitudes has already experienced a decline. There is also a gradual shift towards group research projects (e.g. BOREAS, Global Energy and Water Cycle Experiment) as is encouraged by the granting agencies. Although this may be perceived as a reduction in the support for individual-based research, there are the benefits of interactions among hydrologists and with researchers in other disciplines, necessary in the tackling of broad research questions.

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