GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

Reconstructing geomorphology: an appreciation of the contributions of J. Ross Mackay (1915-2014)

Michael Church
Department of Geography, The University of British Columbia, Vancouver, British Columbia, Canada

ABSTRACT
Based as they are entirely on his own field experiences, Ross Mackay's geomorphological contributions are commonly regarded as the fruit of solo inspiration. In fact, his work is decidedly the product of its time. At the outset of his career, geomorphology was entering a radical transformation from interpretive study of landscape history toward quantitative study of landscape-forming processes. Accordingly, Mackay's earliest works are accounts of regional geography. From 1960, however, his work, following the new perspective, expresses its dominant character: quantitative measurement in the field and on maps, and application of physical theory for interpreting the observations. By 1965 his mature style was firmly established. The outstanding aspects of Mackay's contributions are his genius for making critical field observations and his ability to use them to test geophysical theory. But his early regard for landscape history remained an important aspect of his insight throughout his career.

RÉSUMÉ
Fondées sur des travaux originaux sur le terrain, les contributions de Ross Mackay en géomorphologie sont généralement considérées comme le fruit d'une inspiration unique. Néanmoins, son parcours scientifique reflète aussi l'évolution de la discipline durant l'après-guerre. Rappelons-nous qu'au début de sa carrière, la géomorphologie entrait tout juste dans une transformation radicale qui substituera aux études interprétatives portant sur l'histoire des paysages, des investigations quantitatives des processus de formation des paysages. D'ailleurs, les premières publications de Mackay dans les années 50 sont des comptes rendus de géographie régionale reflétant les paradigmes de l'époque. Néanmoins, dès 1960, ses travaux s'engagent dans la nouvelle perspective qui dominera le reste de son œuvre : celle-ci est fondée sur les mesures quantitatives sur le terrain et sur les cartes, et l'application des théories physiques dans l'interprétation des observations. Dès 1965, ce « style Mackay » était déjà bien établi. Les aspects marquants des contributions de Mackay sont son aptitude à obtenir des observations critiques sur le terrain, puis à les employer pour mettre à l'épreuve des théories géophysiques. Son intérêt initial pour l'histoire des paysages demeurera aussi un aspect important de sa vision de la géomorphologie durant toute sa carrière.

1 INTRODUCTION

Ross Mackay began his scientific career at the close of the nineteenth century. That is because, in geomorphology (and in much of earth science), the nineteenth century continued until about 1950. The great scientific project of nineteenth century earth science was to understand the history of Earth: to comprehend the significance of the rock column as evidence for that history and to understand the historical development of modern landscapes. Work involved mapping and rich description of rocks and topography, and the construction of historical narratives of particular landscapes (Church, 2010). Time scales were geological ones – much too long to admit any detailed consideration of landscape-forming processes. For geographers, the narrative could extend to – or be largely preoccupied with – the people and their means of livelihood in the landscape.

Change began while the world was preoccupied with war. R.A.Bagnold's book, *The physics of blown sand and desert dunes*, based on 1930s explorations in North Africa and published in 1941, announced – right from its title – a radically different way to consider landscape. It was followed in 1945 by R.E.Horton's "Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology", and then, in 1950, by "Equilibrium theory of erosional slopes approached by frequency distribution analysis", written by A.N.Strahler. In 1952, this same author provided the programmatic statement in "Dynamic basis of geomorphology". The new paradigm would seek quantitative expression of landscape-forming processes rationalized in terms of Newtonian mechanics. Landscape history would be made to conform with plausible scenarios of physical process. Time scales would be those of ordinary human perception. While focusing mostly on more local features of the landscape that become directly involved in human works, engineers had been playing this game for centuries, and so many of the methods of study and early results under the new paradigm were directly imported into geomorphology from engineering. With the appearance, in 1953, of Leopold and Maddock's *The hydraulic geometry of stream channels and some physiographic implications*, a work based squarely on engineering regime theory of unlined canals, the mechanistic paradigm was firmly established.

There had, of course, already been geomorphologists who followed a process-focused paradigm, perhaps most prominently the American geologist G.K.Gilbert (1843-1918). Their lead was not followed simply, I expect, because of the dominance in the earlier period of the great historical questions. Ross Mackay's training and early career spanned the period of the revolution in modes of landscape study and the evolution of his style of work reflects the transition. It very much reflects the times in which he worked.

2 EARLY WORK (1947-1960)

Ross Mackay graduated from Clark University (1939) and Boston University (1941), where he would have received a solid geographical training in the older, 'earth history' tradition. After war service he took up Ph.D. studies at the Université de Montréal, where he studied aspects of the late Quaternary history of the Ottawa valley. This issued in two papers in the newly established *Revue Canadienne de Géographie*, "The north shore of the Ottawa River" (1947), and "Physiography of the lower Ottawa valley" (1949). The former is a traditional regional description covering both physical and human geographies of the region; the latter is the core of his Ph.D. thesis. In that work, the principal contribution is a demolition of the view put forward by the French geographer Raoul Blanchard (who founded the Institut de géographie in the Université de Montréal) that terraces in the lower valley and around Montréal are depositional landforms. By their landform association with erosional scarps, by the nonconformable stratigraphy, and by consistency with the postglacial history of degradation in the valley, Mackay showed without doubt that they are erosional features. This work already displayed qualities of his mature contributions: remarkably keen powers of observation; a determination to consider all plausible hypotheses to explain a phenomenon; a penchant to choose the most straightforward hypothesis; a determination to defend the chosen hypothesis by as many independent lines of evidence as possible; and a concern to use historical evidence to the fullest extent possible – habits likely acquired, if not earlier, during his wartime service in Intelligence. But the work also exhibited the character of his training in the earth history tradition. Focused on late Quaternary history of a particular landscape, it invokes the historical-explanatory framework of the period, including the anthropomorphized youth-maturity-old age stages of landform and landscape development.

Upon completion of his Ph.D. Mackay took up his position in the University of British Columbia where he was immediately recruited by the Geographical Branch of the Canadian government to join a small group of geographers engaged in exploration of the Canadian Arctic territories – with the advent of the Cold War a rapidly escalating strategic imperative. This catalyzed his love of the western Arctic landscape and people that set the course for the rest of his career and life.

The publications from his early Arctic seasons are brief and mainly descriptive reports of field activity. However, they reveal a rapid development in the focus of his interests and his method of investigation. Some of his reports, most notably his two major memoirs, written in and immediately following these years (Mackay, 1958; 1963), retain the organization of a traditional regional geography, with sections on geology, physiography, climate, vegetation and human history. The papers, however, begin to focus more narrowly on describing specific landforms and – increasingly exclusively – landforms of permafrost. Thus fissures and mud circles on Cornwallis Island (1953), glacier ice-thrust deformation at Nicholson Peninsula (1956) and on the Yukon coast (1959), oriented lakes at Liverpool Bay (1956), and topography associated with disintegrating glacial ice (1960). (The latter paper was based on notes made during Mackay's first journey north in 1951 when ice conditions forced a week's layover at an anonymous lake in the middle of nowhere – probably the closest he ever came to having an 'adventure'.) Mackay also revealed the wide range of his interests in the Arctic landscape in this period, reporting twice (1957; 1960) on the condition of small boat harbours along the western arctic coast, a topic of considerable interest to the local people and to boat-borne 'outsiders'.

Mackay's regard for historical work is also evident in his early publications, with references to observations and mapping by explorers as diverse as John Franklin (the successful, 1825-27 overland expedition to the Mackenzie Delta), Roald Amundsen (the Northwest Passage expedition of 1903-06); Father Émile Petitot (Oblate missionary and geographer whose late 19th century travels included Anderson River); the Canadian Arctic Expedition (1913-18, led by Vilhjalmur Stefansson, whom Mackay subsequently met); and E. deK. Leffingwell, a pioneer American periglacial geologist whose 1919 USGS monograph Mackay extensively quoted.

3 TRANSFORMATION (1960-1965)

From about 1960, the character of Mackay's work changed radically. Focusing fully on the analysis of periglacial landforms, his work quite suddenly began to reflect the hallmark concerns for quantitative measurement in the field and analysis in terms of physical theory of the new, process-oriented geomorphology. The change in approach might be demarcated from a paper published in 1960 (Mathews and Mackay, 1960; on glacial ice thrusting) or the first pingo paper (Mackay, 1962). It is definitively evident in the content of the Mackenzie Delta memoir (Mackay, 1963). While the change appears relatively abruptly, it seems to have been gestating in Mackay's mind throughout the latter 1950s as he read the evolving literature and considered how best to approach the analysis of the periglacial landforms he was describing.

Mackay never discussed the methodological or philosophical motivations for his work so, to get beyond invoking the spirit of the times, one must speculate on the wellsprings of his conversion. One probable encouragement was work with his UBC colleague William H. Mathews, lead author of the 1960 paper. Mathews, one of the last professional geologists of renaissance proclivities, was trained in physics and geological engineering: he was well prepared to place glacial ice thrusting – described by Mackay in earlier papers – on a theoretical and quantitative foundation. The 1960 paper is one of the very few of Mackay's papers in which he is not the lead or sole author, attesting to Mathews's influence on this work. It surely demonstrated to Mackay the route to quantitative analysis of landforms. The two friends subsequently collaborated in a range of studies of snow creep, needle ice occurrence and patterned ground phenomena in the mountains near Vancouver. Their joint work may never have come about but for the circumstance that, before 1959, Geography and Geology were practiced in a single department at UBC.

An influence of similar character may have been the pioneering textbook by S.W.Muller (1945; 1947), *Permafrost or Permanently Frozen Ground and Related Engineering Problems*. This book, of which a copy was held in the UBC Geology library, summarized extensive Russian experience of permafrost along with the more sporadic (to that time) European and North American work. It provided Mackay with an overview of the history of technical studies of the subject, mostly conducted by engineers in a process-focused perspective. It particularly emphasized the response of permafrost to ground surface disturbances, such as the construction of buildings and roadways. It also gave extensive tables of the geotechnical properties of frozen ground developed by Russian engineers. Reference to the book appears in Mackay's papers of the period, notably the 1960 ice-thrust paper and the 1963 Mackenzie Delta monograph.

The primary influence prompting the change in Mackay's style, however, was his reading of the literature and his own quick intelligence. He not only picked up the spirit of change, he mined the literature he was reading as a source of ideas for application to understand permafrost and its attendant phenomena. In the 1950s it was still possible to keep track of the literature of the entire field of geomorphology and, accordingly, Mackay found inspiration in a surprisingly wide range of sources. This is best illustrated by a reading of the Mackenzie Delta memoir (Mackay, 1963), in which he repeated the pingo analysis of 1962 and introduced a number of new, theoretically grounded analyses.

He returned to the oriented lakes he had described in 1956, borrowing theory on equilibrium shoreline form from the American coastal engineer P. Bruun (1953), developed and applied to oriented lakes on the Alaskan north coast by R.W. Rex (1961) to show that the lakes were shaped by winds dominantly blowing across (perpendicular to) the long axis of the lakes (a formerly controversial issue). Characteristically, Mackay conducted extensive numerical exercises to confirm the cross-wind hypothesis, and he methodically considered and discarded alternate explanations that had been put forward, mostly by invoking his own meticulous field observations.

The occurrence and growth of massive sheets of ground ice were analyzed by application of Stefan's solution for freezing of ice lenses, put forward in the context of freeze and thaw by the American geotechnical engineer K. Terzaghi (1952) and detailed in engineering textbooks of heat conduction consulted by Mackay. But he first used his own field observations to dismiss the possibility that massive ice, including ice exhibiting deformed bedding, was relict glacier ice or buried sea ice.

The analysis of the development of 'closed system' pingos is the most elaborate theoretical exercise that Mackay conducted. The basic concept of upward water expulsion from a freezing thaw bulb beneath a shoaling lake (or in a former lake basin) was advanced by A.E. Porsild (1938) and elaborated by F. Müller (1959). Mackay developed the theory mathematically by adapting analysis by the American geophysicist A.H. Lachenbruch (1957) for heat conduction in permafrost beneath heated buildings. (Unlike most geomorphologists of the period, Mackay was competent in applied mathematics.) A lake that does not freeze to the bottom is analogous to a building placed on frozen ground. Once the lake is removed (or shoaled to the point that it does freeze to the bottom) frost begins to prograde into the subjacent thaw bulb (talik). The lateral margins being frozen and water escape denied below by frost, saturation or impermeable strata, the remaining water is subjected to increasing pressure as the saturated ground in the shrinking thaw bulb expands upon freezing. Water expulsion then occurs upward towards the thinnest confining layer, which is deformed in response to the hydraulic pressure. The escaping water freezes under the deforming soil cap to form the pingo. All this was laid out in full mathematical detail by, in effect, inverting Lachenbruch's analysis. The process and predicted patterns of pingo growth were abundantly confirmed by Mackay through often ingenious observations during much of the rest of his career.

Perhaps the most startling example of Mackay's ability to borrow and repurpose prior analyses lies in his analysis of Mackenzie Delta river channels – startling because he did not before or subsequently dwell on the topic, and it is not intrinsically a periglacial topic. Yet it seemed called for in an analysis of the physiography of the Mackenzie Delta. In the absence (in 1960) of any hydrological or hydrographic measurements of the river, he considered aspects of the Delta channels that could be measured from maps, including channel widths, junction angles, and meander-form. He adopted 'expected' relations amongst these variables from work by C.C. Inglis (1949) and by L.B. Leopold and M.G. Wolman (1960). Inglis was a British civil engineer engaged in the design and management of unlined 'regime' canals and long-time Director of the Poona hydraulics research station in British India; Leopold, an American engineer and geologist who was Chief Hydrologist and Director of the Water Resources Branch of the United States Geological Survey. Following their lead, Mackay explored various morphometric relations amongst elements of the channels' geometry and found that the Delta channels are generally relatively narrower than channels elsewhere. He supposed that the contrasting summer and winter (sub-ice) flow regimes may be a reason for that.

Two aspects stand out from the foregoing accounts of Mackay's inspirations and analyses: first, they were all firmly grounded in his own field and map observations and, second, they all drew inspiration from engineering analyses or, at least, analyses by engineers of analogous situations – a process described by his colleague, J.K. Stager of 're-ordering of the known to unravel the unknown'. These are exactly the hallmarks of the 'new' geomorphology of the 1950s and 1960s. Ross Mackay led in permafrost studies the development of a style of work, designed to reveal the details of landform genesis, that his contemporaries were leading in other branches of geomorphology. There is often a resemblance in *modus operandi* amongst these geomorphologists. A striking example arises in a comparison of the methods employed by Mackay and those of L.B. Leopold who, as chief of the USGS Water Resources group, led the early reinvention of fluvial geomorphology. Both gave absolute primacy to field observations; both were keen observers; both borrowed physical theory – usually theory adapted for engineering purposes – to analyze and provide rational explanation of their findings. So far as I know, they never met.

4 MATURE WORK (from 1965)

Following the emergence of his propensity to view landforms in genetic and theory-based terms, Mackay's work assumed its mature form: painstakingly detailed and often ingeniously arranged field observations directed toward providing critical evidence to decide amongst alternative, theory-based hypotheses for the origin and development of the landform. Essentially all of Mackay's papers have their basis in field observation or, in a few papers, laboratory investigations of frost heave.

The single exceptional paper, however, represents perhaps the most outstanding example of his ingenuity. That is 'Glacier flow and analogue simulation' (1965). In that paper he appropriated an analogue electrical field plotter to model the flow patterns of the North American Pleistocene ice sheets on the basis that both phenomena are driven by flow down a potential gradient. The results are entirely plausible as a reflection of the large-scale features of the ice sheets but, so far as I know, they have never been followed up.

4.1 Scope of work

The range of phenomena that attracted Mackay's interest continued to expand in the early mature years. He initiated work on permafrost depth, on the annual cycle of freeze and thaw in the active layer, and on frost features in the active layer. He made the most detailed studies of massive ground ice and of ice wedges and published an authoritative classification of ground ice (Mackay, 1972). He made studies of freeze-up and breakup along Mackenzie River and of the mixing of Mackenzie River waters with those of its tributaries (mixing of waters was a heavily researched topic at the time), principally Liard River, for which purpose he twice canoed the length of Mackenzie River. With W.H. Mathews he continued to investigate the Quaternary history of the Mackenzie region. All the while he continued his investigations of pingos. A hallmark of his papers is that each one focuses on a single landform or a single aspect of environmental process or environmental history. Yet in the field he was simultaneously pursuing a number of projects.

4.2 Observation

The principal basis for Mackay's success was his remarkable power of observation. But he was ingenious in finding ways to extend his observations (Mathews, 1985). A remarkable example was his use of cheap, battery-powered watches that display the day and week to determine the time of ice wedge cracking. He rewired the battery via a breaking wire across the crack position. The combination of date and day when the watch stopped is unrepeated for seven months, giving him an unequivocal and precise time of cracking. Several such installations positioned along a crack yielded the speed of lateral crack propagation. Multiple breaking wires buried in the active layer gave evidence of the origin and direction of vertical propagation of the crack.

To determine the geometry of frost cracks Mackay attached spheres of known diameter to a stiff measuring tape and inserted them into the crack to refusal. He thereby learned the width of the crack at the known depth. He used these technical innovations to test the theoretical prediction by Lachenbruch (1962) that cracks originate at the top of the ice wedge (and base of the active layer). Mackay (1974) surmised from evidence of 'multistorey ice wedges' that Lachenbruch was correct; ten years later (Mackay, 1984a) he presented direct evidence from his breaking wires that upward cracking occurs about two-fifths of the time (and can propagate into the overlying snow).

4.3 Collaboration

Ross Mackay was by nature inclined to pursue his research independently. He did not normally collaborate directly with his graduate students and, aside from his colleague, Mathews, he made few joint investigations. Early in his career he published jointly with his field assistant (and later colleague) J.K. Stager, and he pursued freeze-up/breakup studies with his sometime student D.K. Mackay. He also sought and obtained collaboration with specialist scientists when he needed particular results. Hence he worked with the isotope chemist H.R. Krause to obtain isotope analyses of river water and ice; he collaborated with the palynologist J. Terasmae to examine Holocene pollen, with the palaeontologist F.J.E. Wagner for mollusc identifications, and with various geophysical colleagues at the Geological Survey of Canada for remote sensing and coring of ground conditions. He frequently took academic colleagues to the Delta on his winter trips. Finally, late in his career he collaborated with his former postdoc, C.R. Burn – his only postdoctoral student.

4.4 Experimentation

Experimental evidence is considered to be the acme of scientific endeavor. It leads to unequivocally interpretable results. So it was natural that experimentation should attract Mackay's attention. However, experimentation in field science is not easy: it is not superficially obvious that environmental conditions can be sufficiently well controlled for experimental purposes. One may argue, however, that control of boundary and initial conditions is sufficient, that in fact the normal continuation of forcing conditions (weather) is appropriate in field experimentation (Church, 2011).

Mackay may have had experimental possibilities on his mind from his earliest Arctic visit for, late in his career, he published a study of ventifacts at Paulatuk that extended from his first season (1951) to 2003 (Mackay and Burn, 2005). He attempted to discern changes over 52 years to 158 natural rocks of varying lithology. To the extent that this was 'experimental' work it was an inadvertent experiment. Another inadvertent experiment began with a fire near Inuvik in 1968. Mackay quickly established sites to study the response of the active layer, contrasting burned sites with control sites beyond the perimeter of the fire (Mackay, 1995).

Mackay's first deliberate experiment was his most spectacular one. Observing seasonal inflation and deflation of pingos on the order of 10-30 cm by means of survey, he hypothesized that the expulsion of water from the freezing bulb beneath the pingo accounts for the inflation. He then drilled into one pingo to release the expected water pressure, obtaining a satisfactorily artesian water spout to confirm the hypothesis (Mackay, 1977).

In the field he manipulated snow cover using fences to study the effect on ground temperature and on ice wedge cracking. In the laboratory, in a more conventional experimental mode, he studied frost heave by upfreezing from below (Mackay, 1984b).

His most ambitious experiment, however, was the artificial draining of a lake, "Illisarvik", to study the progradation of permafrost into the lake bottom and the development of ground ice features (Mackay, 1997). In this endeavor he was repeating an event that has happened countless times along the retreating coast of the western Arctic. He had long before noted the correlation of pingo occurrences with shallow depressions and reasoned that drained lakes, formerly sufficiently deep not to freeze to the bottom, provide the ideal conditions for pingo growth. No doubt he hoped to grow a pingo, and now the site indeed has done so (C.R. Burn, personal communication; May, 2015).

4.5 Publication

Ross Mackay was universally recognized within the permafrost and periglacial community as the premier investigator of his time. But he was not nearly so well known in the larger scientific, or even earth science, community as his achievements merit. A reason for that is his loyalty to his own supporters. Throughout his Arctic career he was supported by the Geographical Branch and then the Geological Survey of Canada, both units of Canada's national earth resources ministry (which has had several names over the course of Mackay's career). Accordingly, he published in the *Geographical Bulletin* (house journal of the Geographical Branch), in *Current Research* (the research-in-progress serial of the Geological Survey), and in the *Canadian Journal of Earth Sciences*, Canada's national earth science journal. They are all good journals, but not major international journals. He published but once in *Science*, and very occasionally in other international journals. But he did not deliberately attract attention to his own achievements.

5 LEGACY

Ross Mackay has left behind a towering set of results in periglacial geomorphology. Always working from field observation and using his observations to test the application of analytical theories on heat and water transfer under temperature gradients and at freezing fronts, he constructed a body of fundamental results that will remain current for decades. At the same time, he introduced periglacial geomorphology to quantitative and theory-based discipline.

We have considered how a revolution in the approach to earth science in the 1950s appears to have set Mackay on his course. A second revolution has occurred within the length of his career. Beginning in the 1970s, and gathering strength from the 1980s on, earth science has increasingly come to be recognized as a 'system science', an endeavor to understand earth processes as the result of interaction amongst numerous subsystems. Nowhere is this more evident than at Earth's surface, with its intersection of climate, hydrology, biotic processes, environmental chemistry and physical processes. The means to analyze the interactions amongst these elements is increasingly by numerical modeling – modelling that characteristically mixes analytical and empirical results. The model increasingly replaces closed form theory as the summary of our understanding of the environment. Important characteristics of Mackay's work, however, are that he focused his attention on one phenomenon at a time, and he always approached analysis of his observations using classical analytic theory, supported by statistical analyses to encompass the range of natural variability in the phenomena that he measured. He took no part in the system perspective. He had found a successful way to understand a part of nature that held endless fascination for him, and he remained loyal to that way to the end.

ACKNOWLEDGMENTS

Thanks to Michel Lapointe, Olav Slaymaker and John Stager for reviews and corrections of the paper, and especially to Chris Burn for a thorough review and for insights into Ross Mackay's career.

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